ECFA Higgs Factories: 2nd Topical Meeting on Reconstruction

Reconstruction Needs for LLP

Juliette Alimena, Rebeca González, Jan Hajer, Marcin Kucharczyk, Emma Torró, Sarah Louise Williams, Filip Zarnecki

Introduction

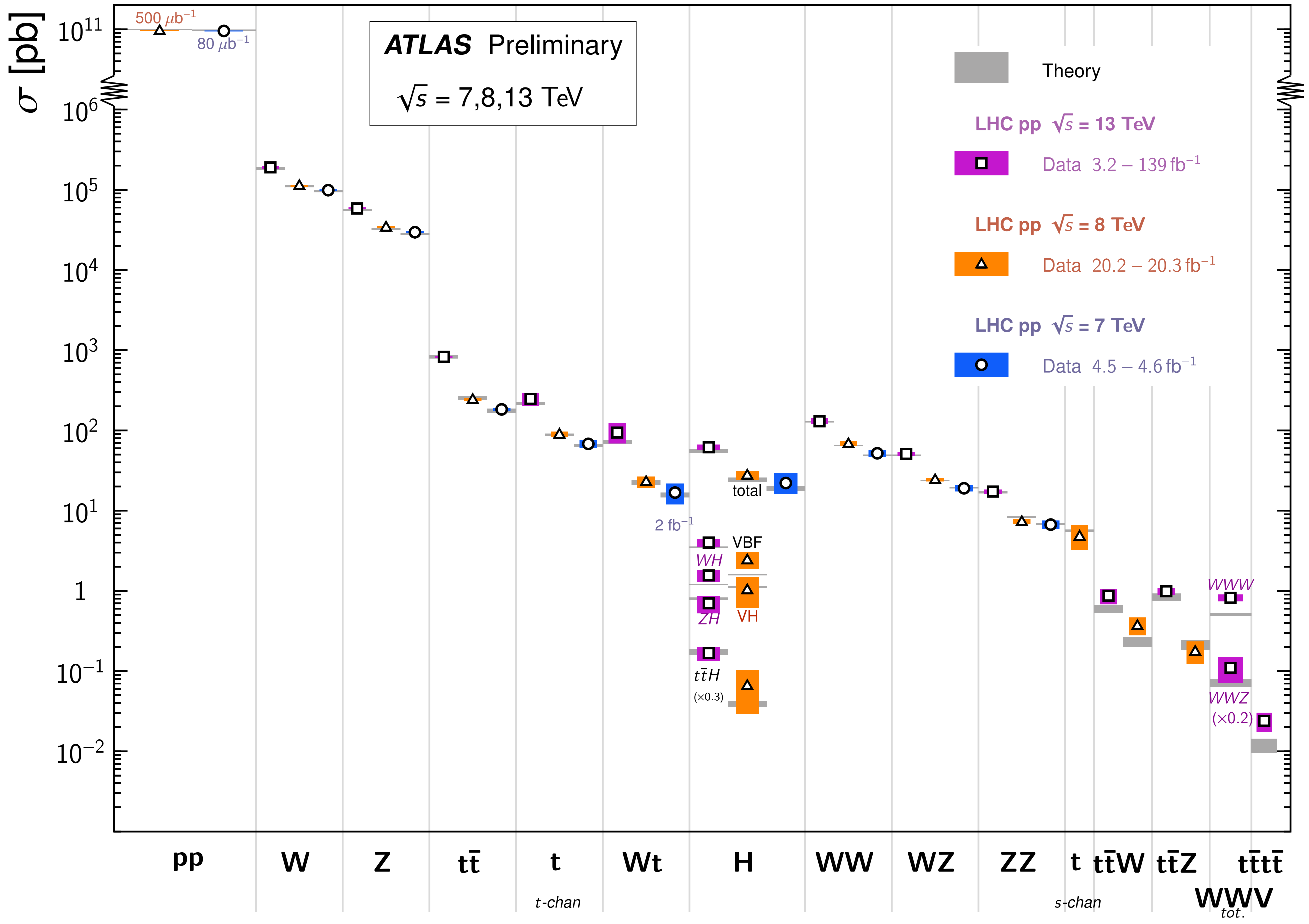
- Standard Model (SM): very successful theory
- Precise predictions, verified by experiment with impressive agreement with theory across orders of magnitude

- Cannot be the ultimate theory
- Several open questions in HEP

- What is Dark Matter?
- Neutrinos have a mass ≠ 0
- Why is the Higgs so light? Hierarchy problem
- Matter and antimatter are not symmetric
- …

Standard Model Total Production Cross Section Measurements

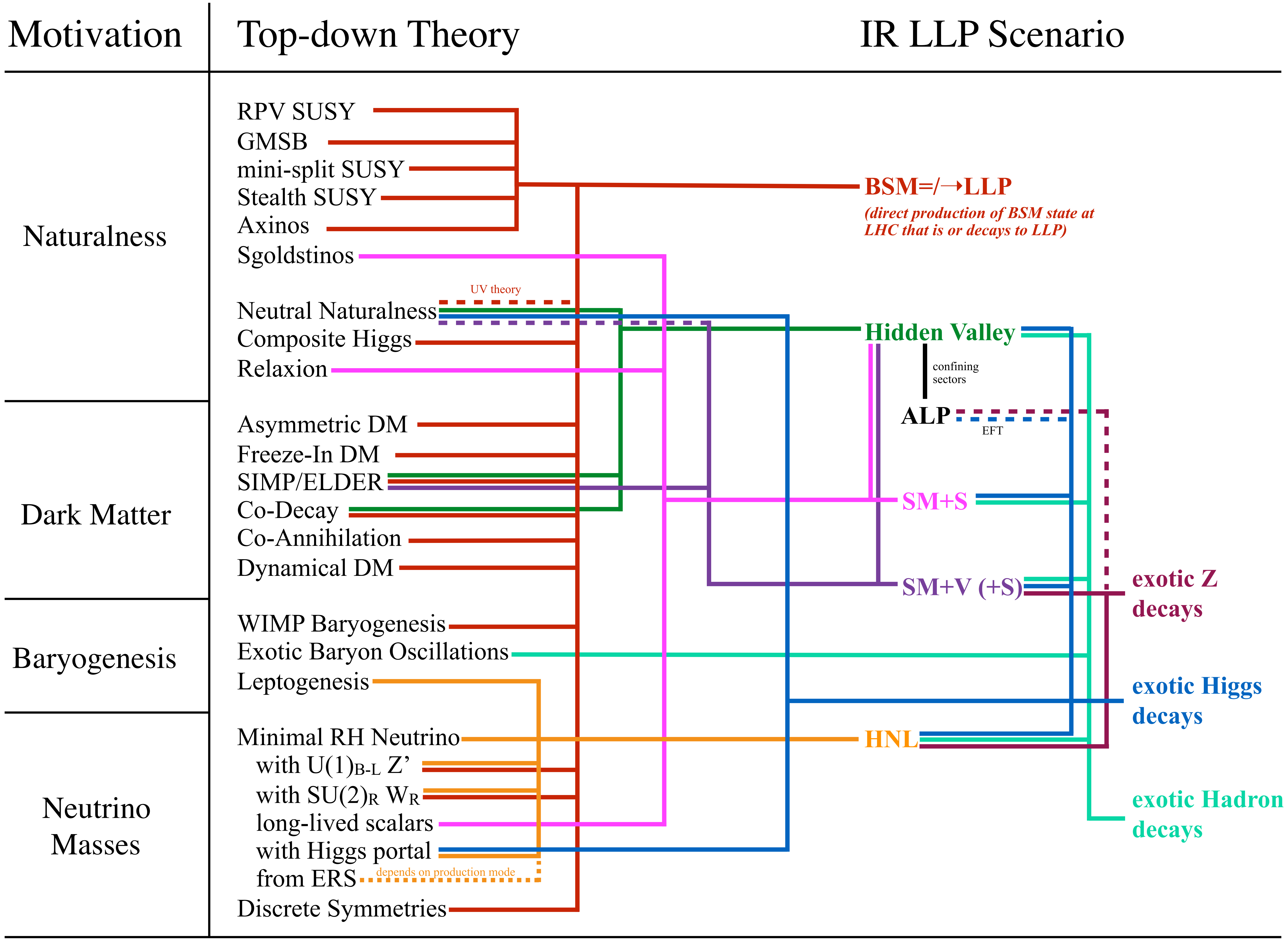
Status: February 2022



Introduction

New physics could have long lifetimes

Signatures not visible in standard HEP searches!!



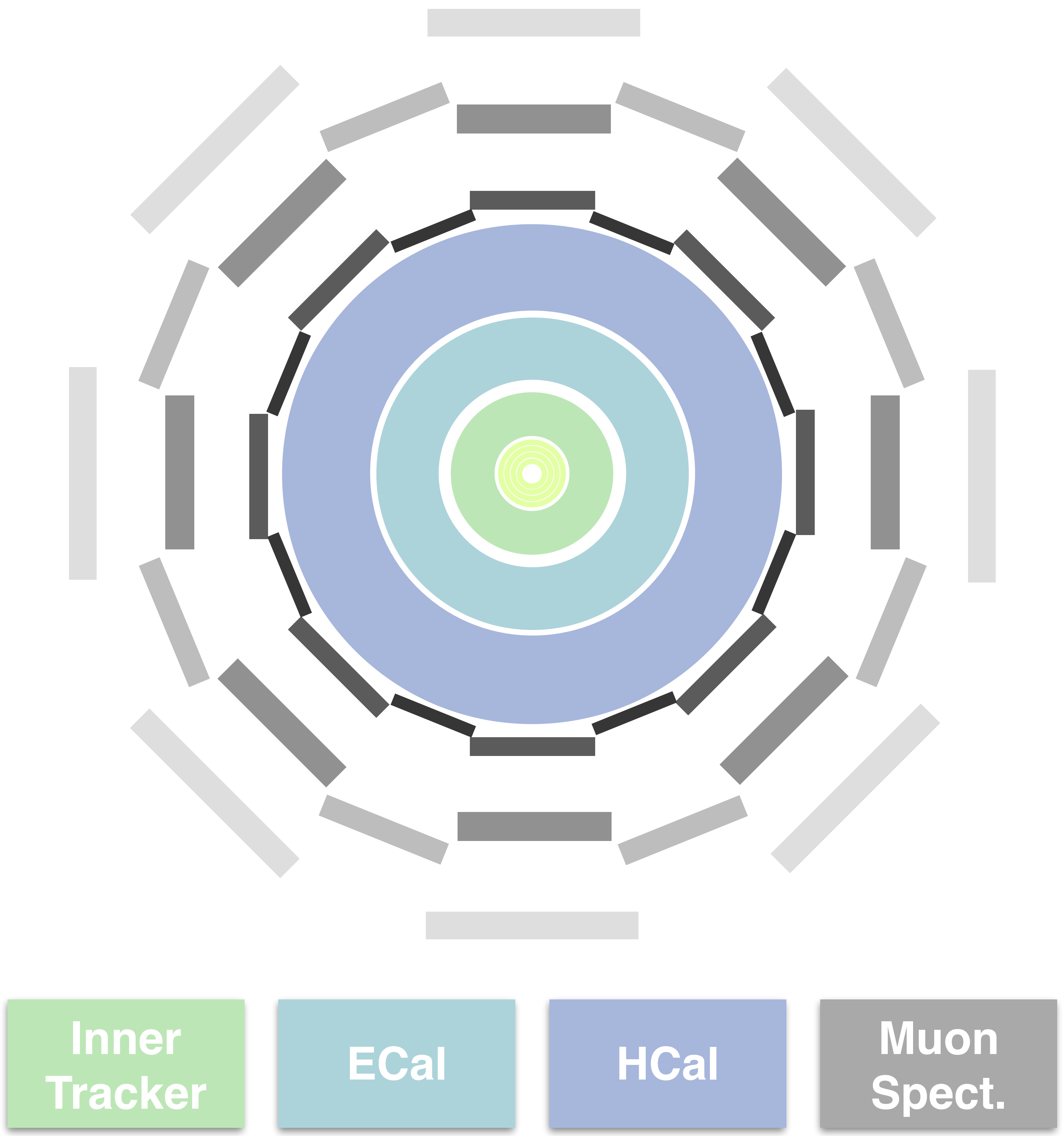
Curtin et al, 1806.07396

How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime

Standard HEP detector structure



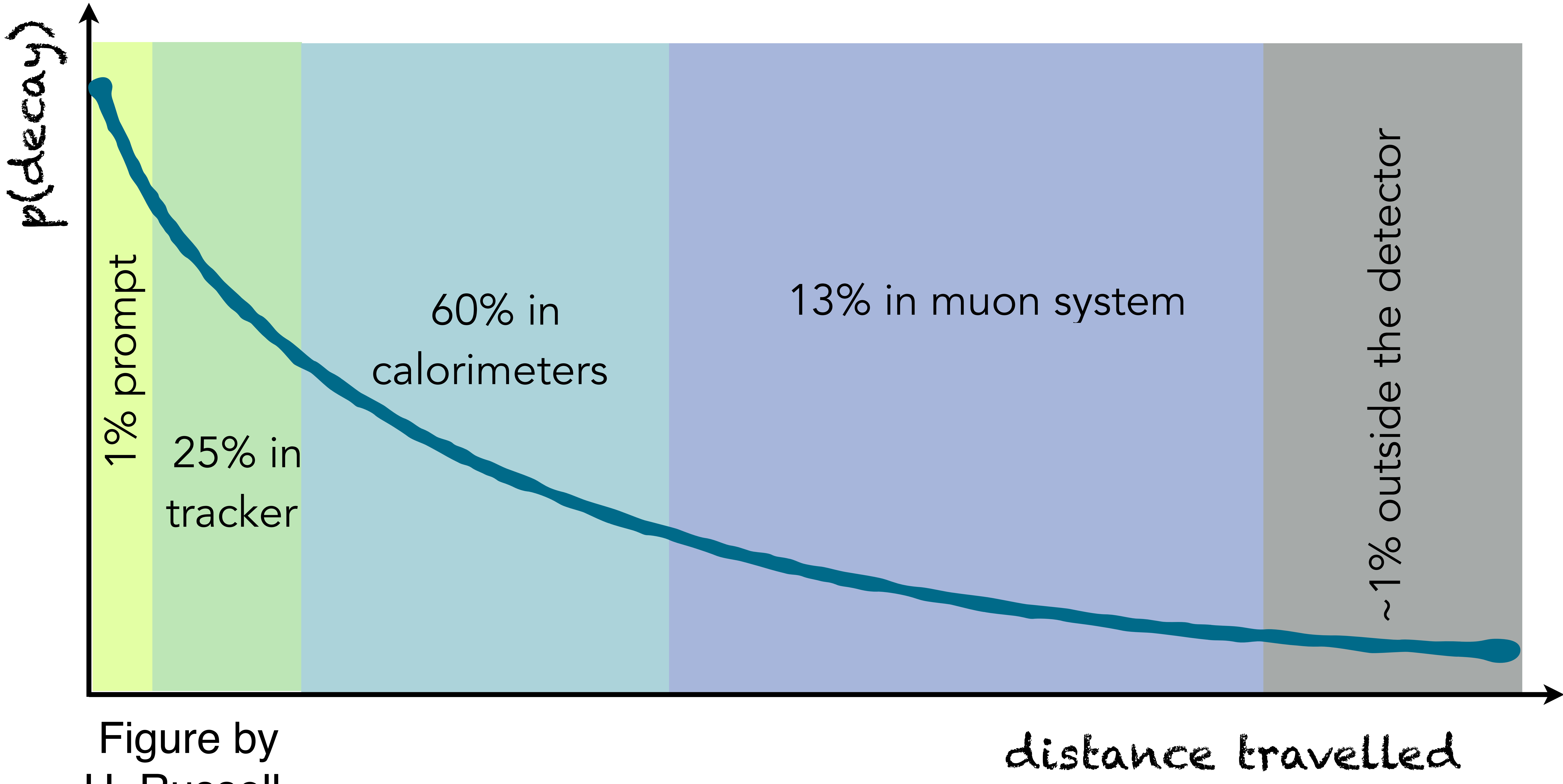


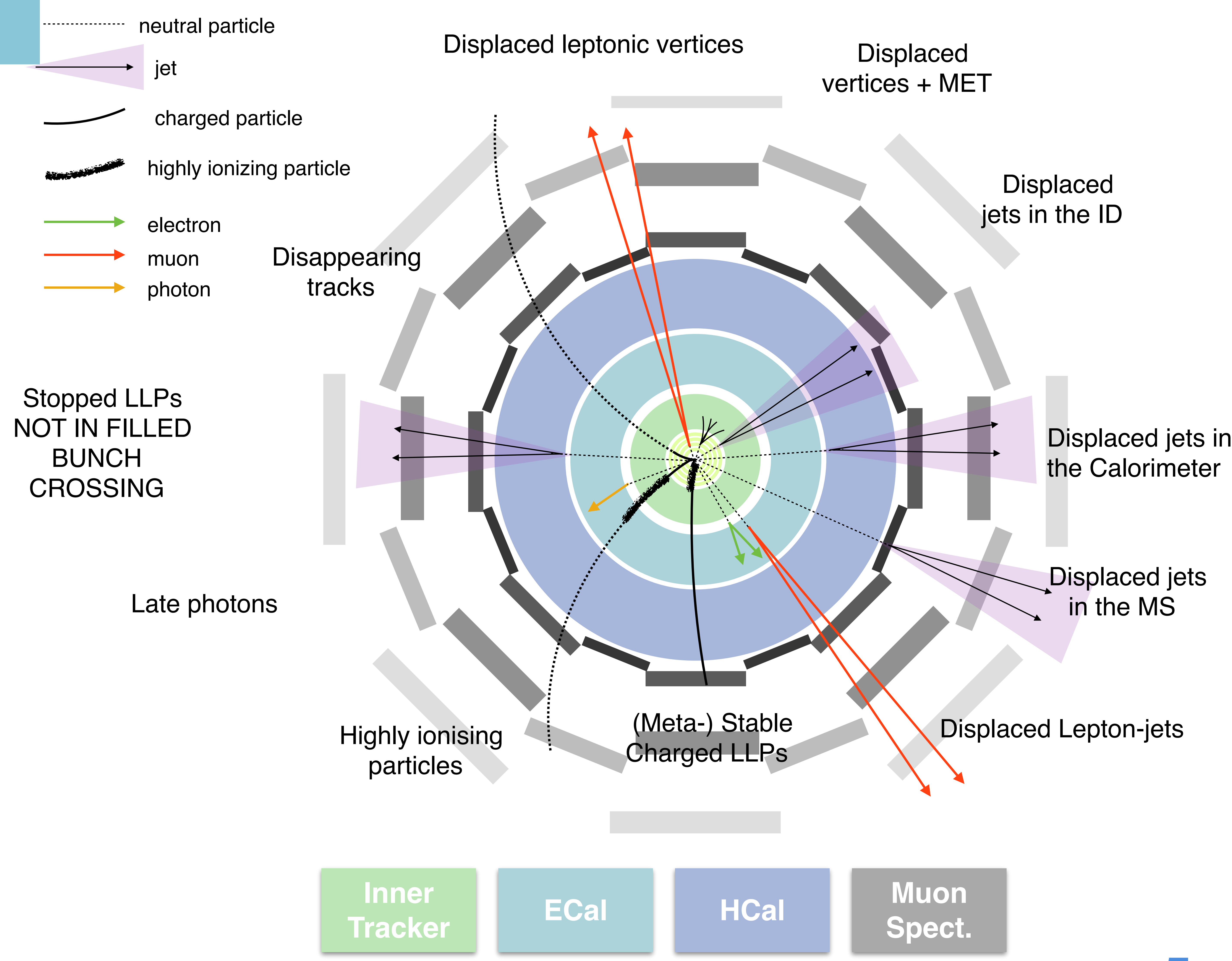
Figure by H. Russell

How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime | LLP nature | object identification

- Is it charged?
  - Does it leave a standard track?
  - Is it highly ionising?
- Is it neutral?
  - which decay mode (hadronic, leptonic, photons, invisible)?



- None of these signatures would be "seen" by a standard HEP search!

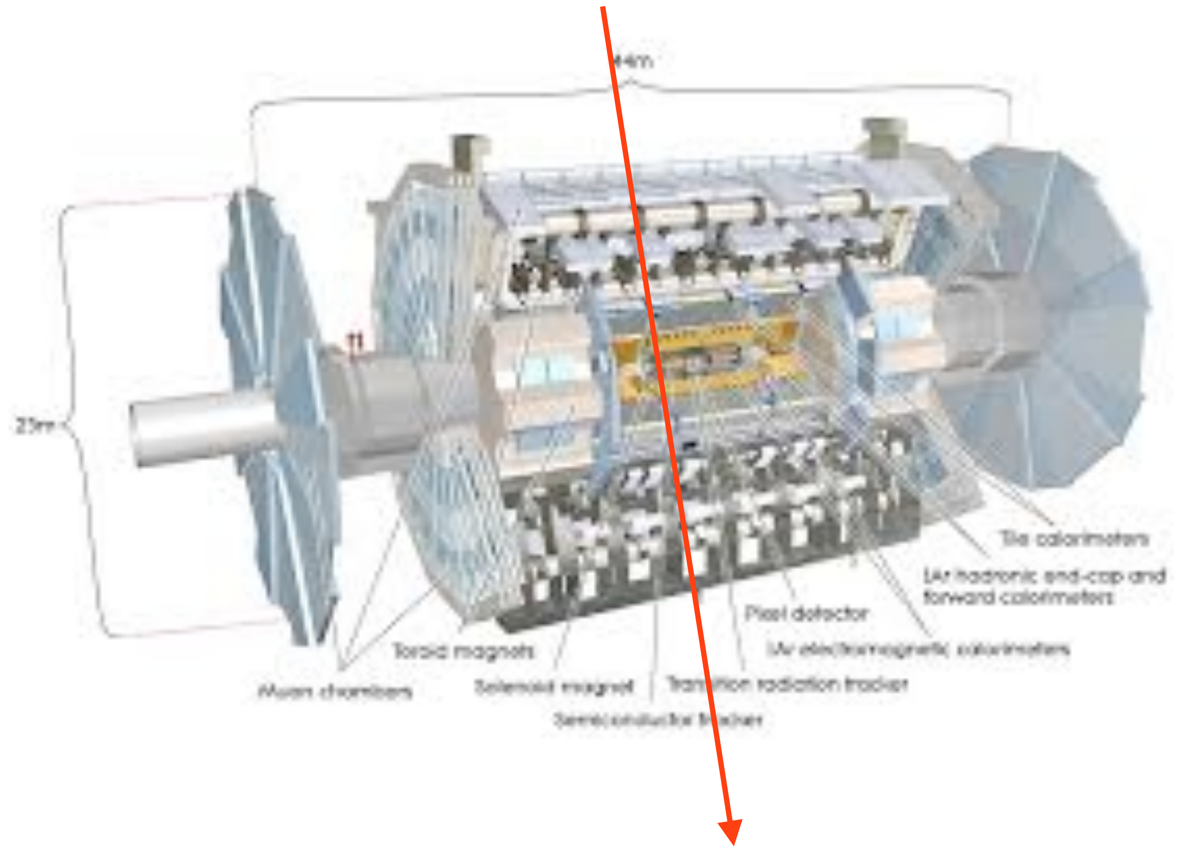
How can we look for LLPs in collider experiments?

That depends on:

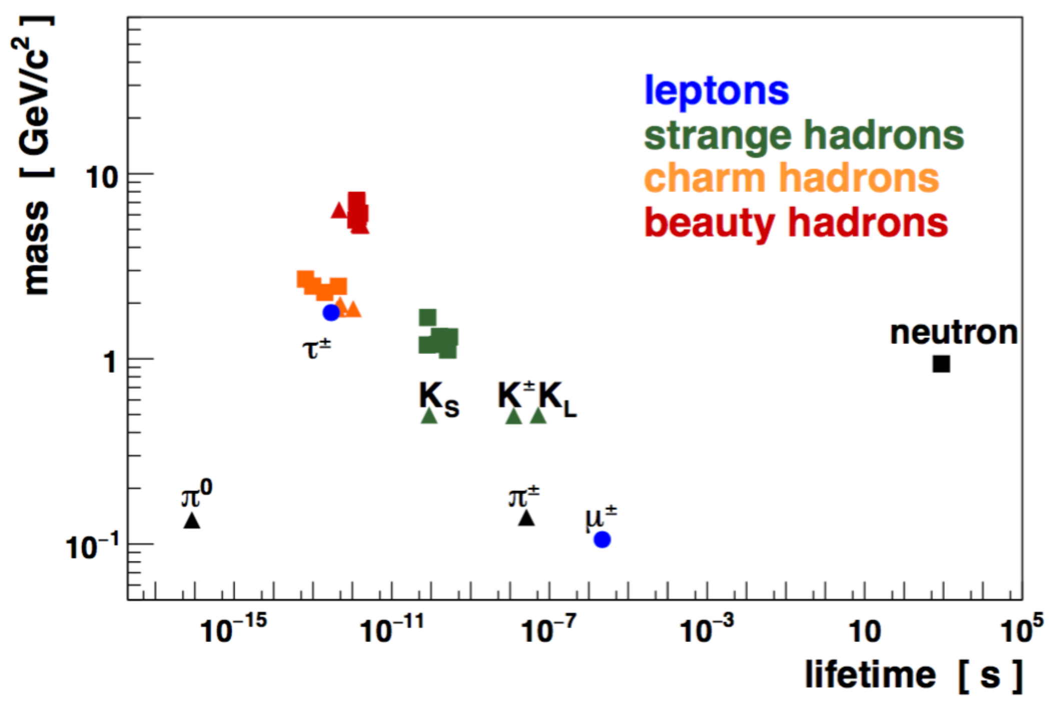
LLP lifetime	LLP nature	object identification	Background rejection

- Small or unusual backgrounds play a key role:

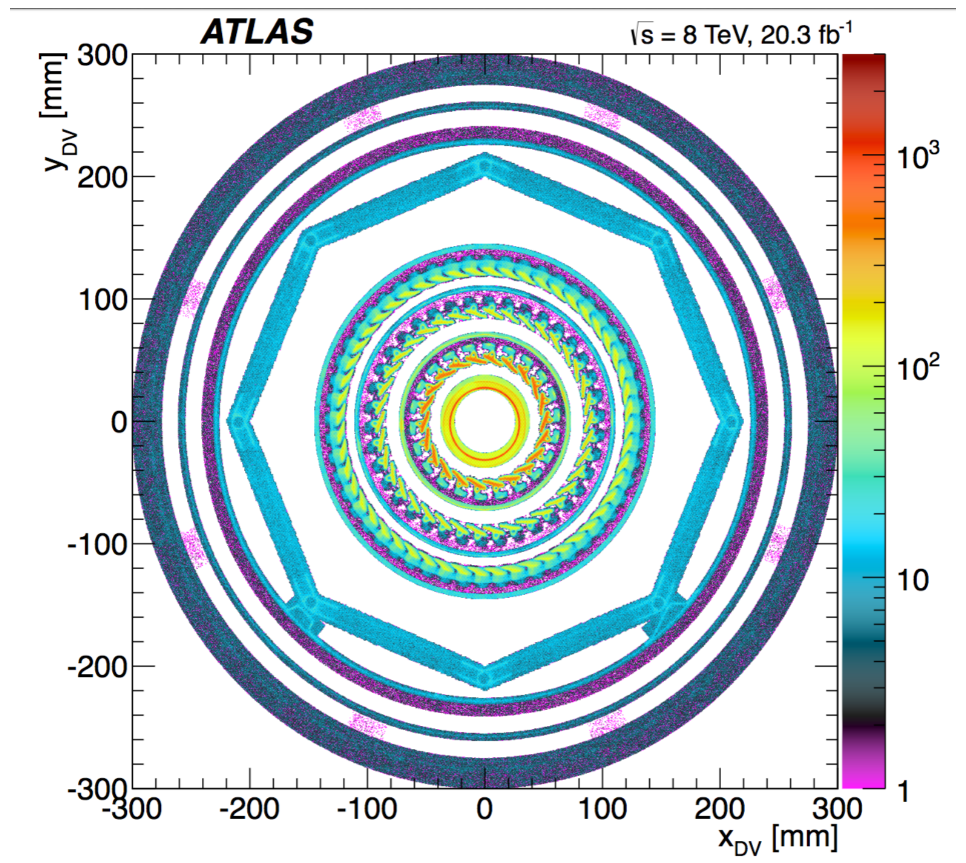
cosmic muons



SM particles with relatively long lifetime



material interactions



- Need very good background identification
- For most of them, no good simulations
  - All searches rely on data-driven methods

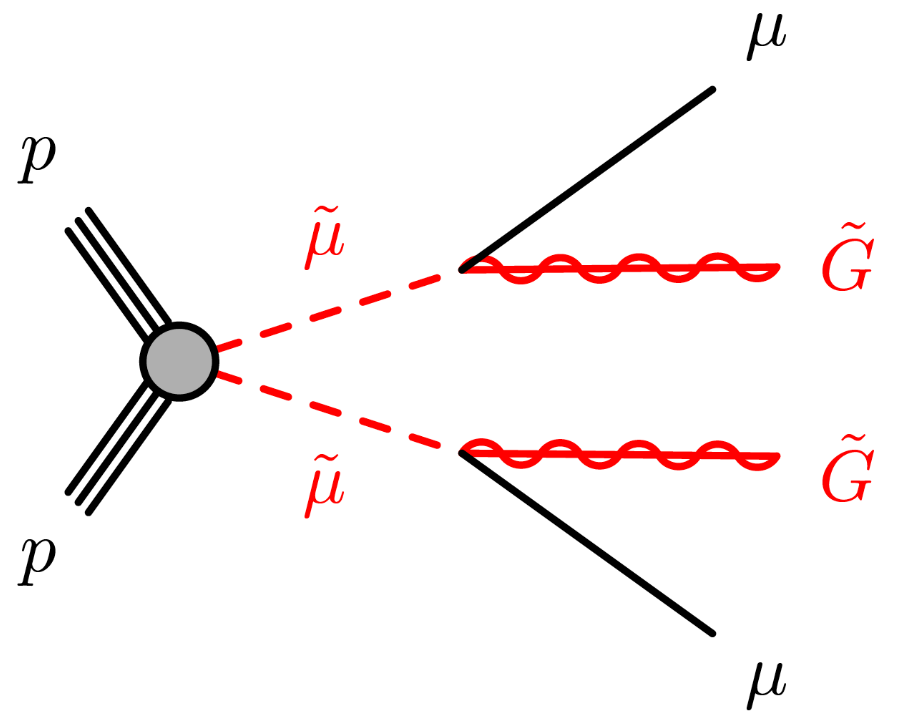
LLP lifetime | LLP nature | object identification | Background rejection

Reconstruction studies on specific signatures

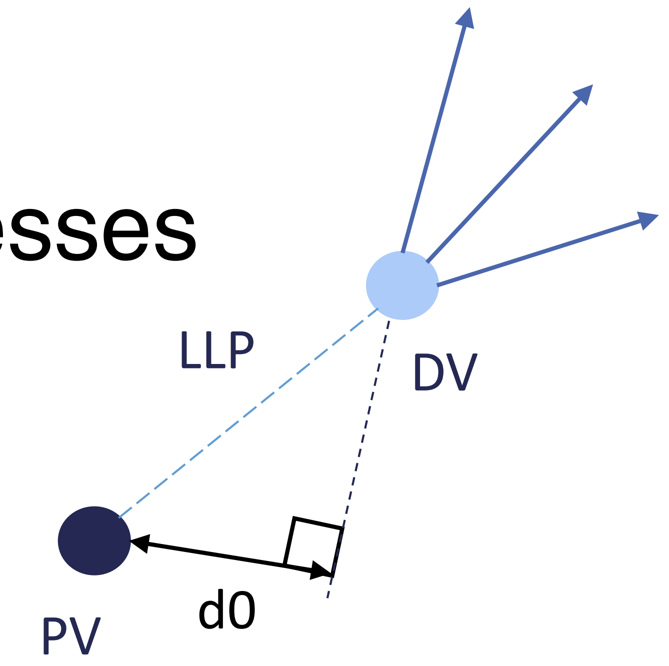
Tracks with large impact parameters

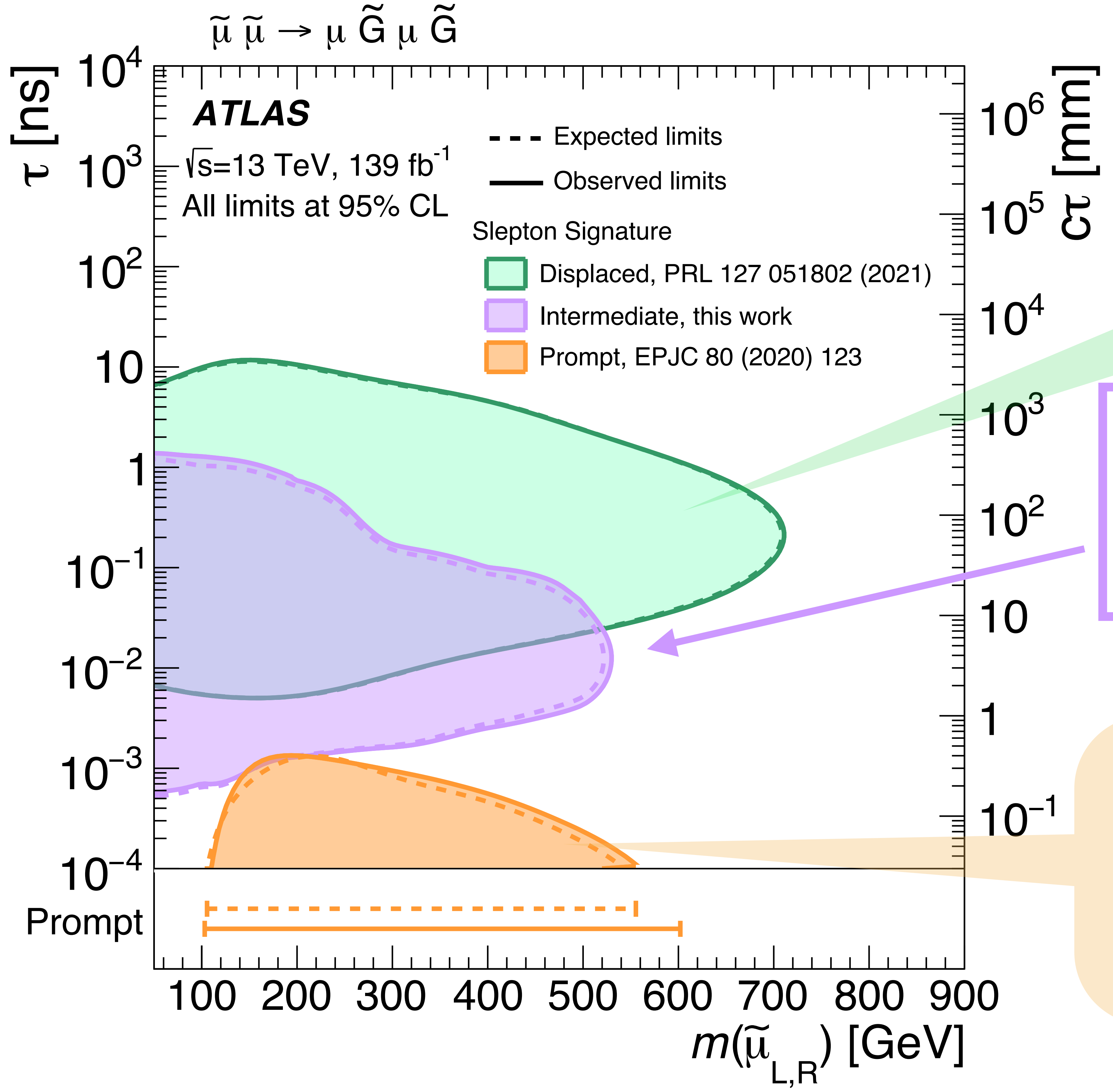
ANA-SUSY-2020-09

ATLAS Micro-displaced muons



- Search for pairs of opposite charge muons with O(mm) impact parameter
- GMBS SUSY with nearly massless gravitino LSP and long-lived slepton ($\tilde{\tau}$, $\tilde{e}$, $\tilde{\mu}$ NLSP) due to small coupling to the LSP
- Signal Regions defined with large transverse impact parameter $|d0| > 0.6$ mm
- Dominant SM background: semileptonic B-hadron decays, $bb \to \mu\,\mu$
  - $|d0| > 0.1$ mm to reduce SM processes





Specific search for decays in the ID

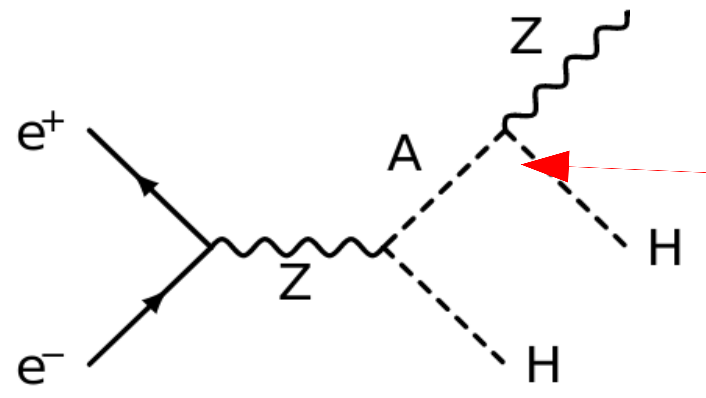
Closing the gap between prompt and large displacement searches

Prompt search reinterpreted in LLP scenario

Tracks with large impact parameters

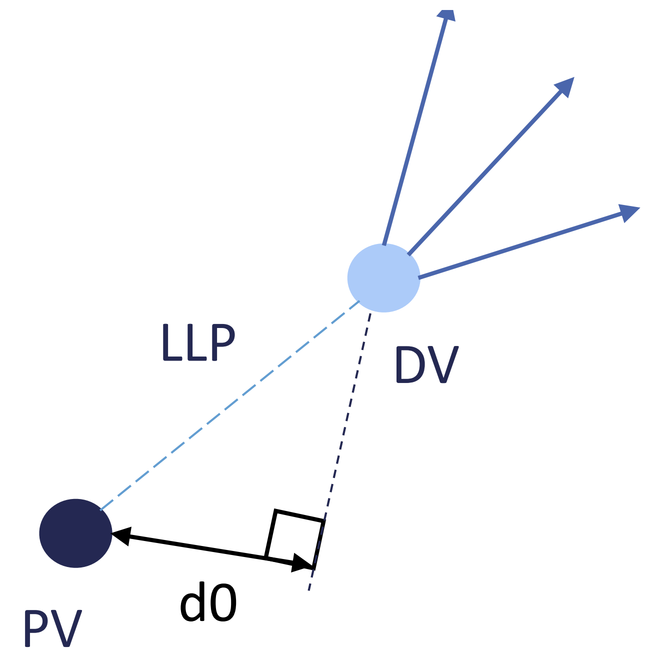
Studies at ILD

As a challenging case (small boost, low-pT final state) we considered:
→ (tuned) Inert Doublet Model sample with small mass splitting,



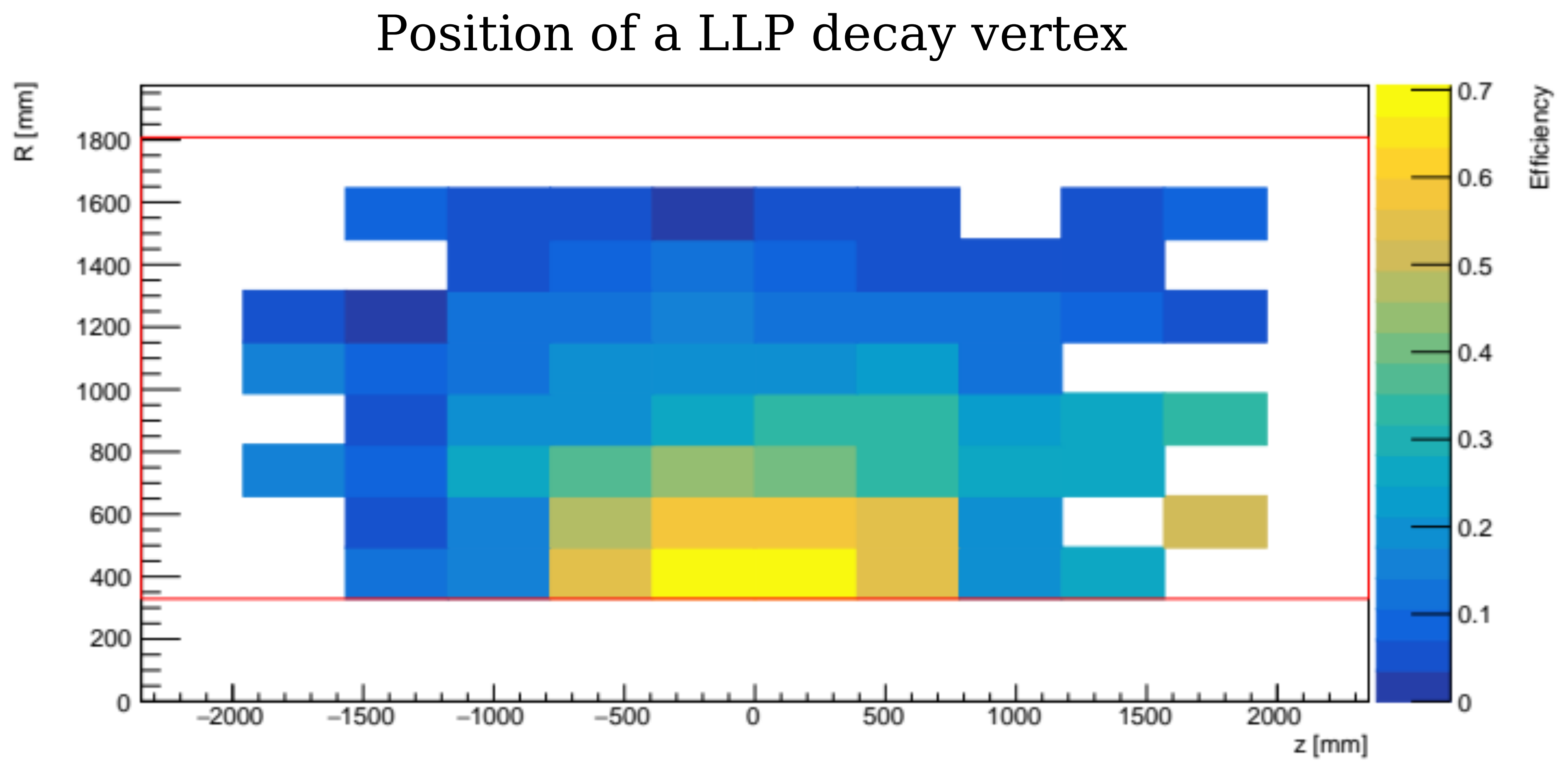
Long-lived, with $c\tau = 1\,\mathrm{m}$

$m_A - m_H = 1, 2, 3, 5\,\mathrm{GeV}$

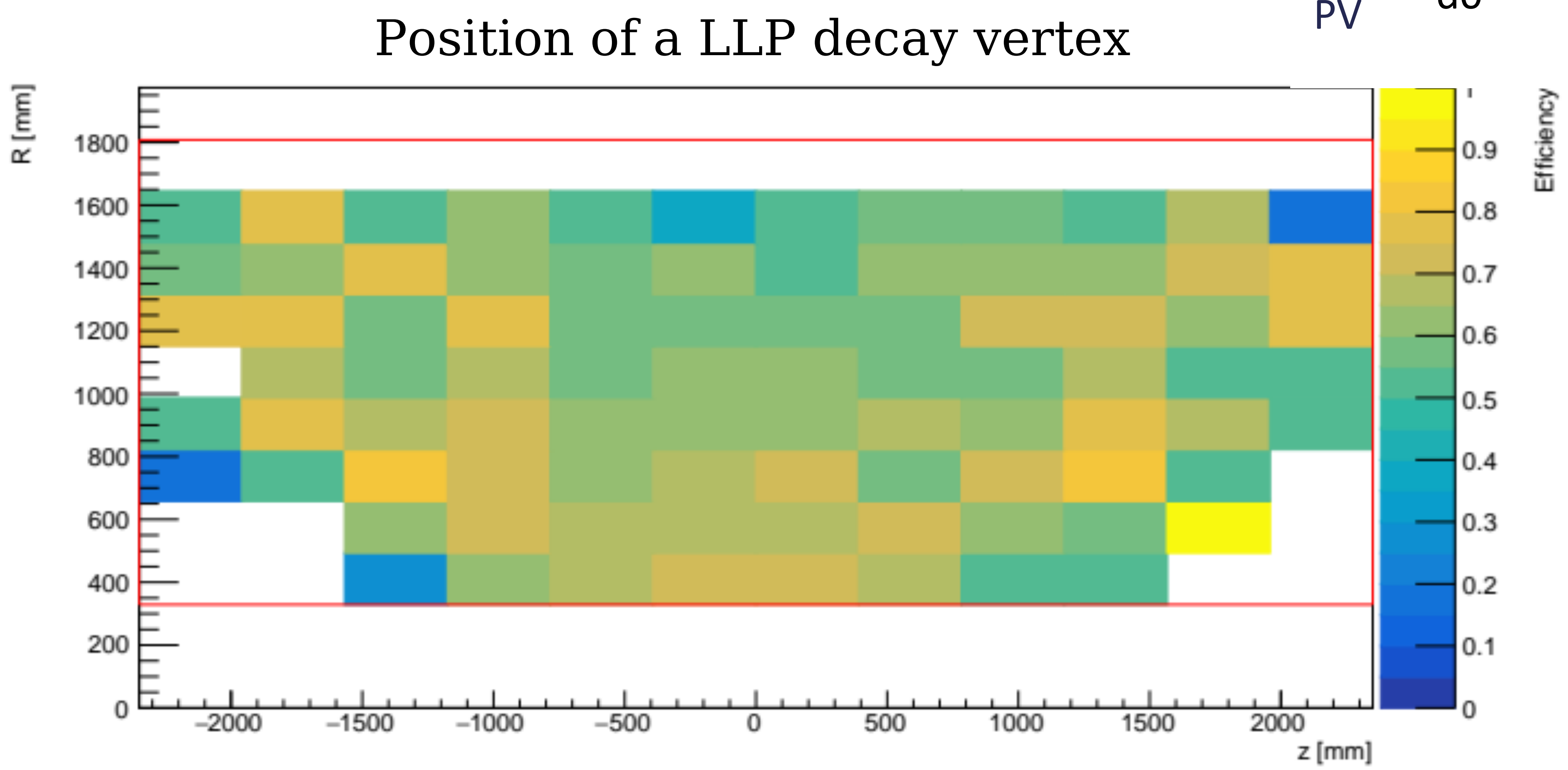


- Default cuts in track reco: d0, z0 < 500 mm
  - Strongly suppresses reconstruction of LLPs in the inner tracker!
  - Removal (or loosening) of impact parameter cuts: great efficiency recovery

- Default d0, z0 cuts



- No d0, z0 cuts



$\Delta m_{AH} = 1\,\mathrm{GeV}$

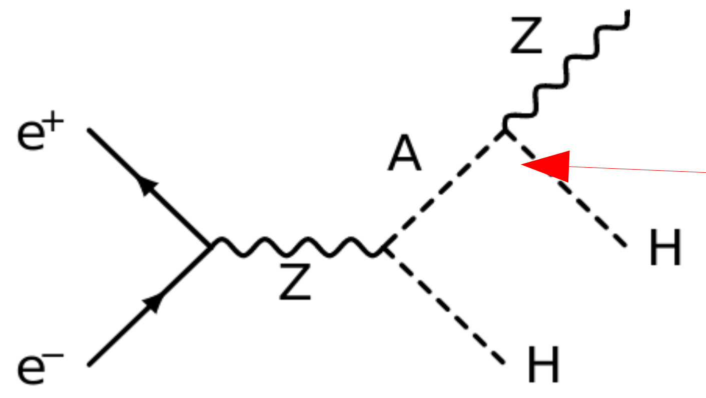
From Jan Klamka

Tracks with large impact parameters

Studies at ILD

As a challenging case (small boost, low-pT final state) we considered:

→ (tuned) Inert Doublet Model sample with small mass splitting, $Z^* \to \mu\mu$

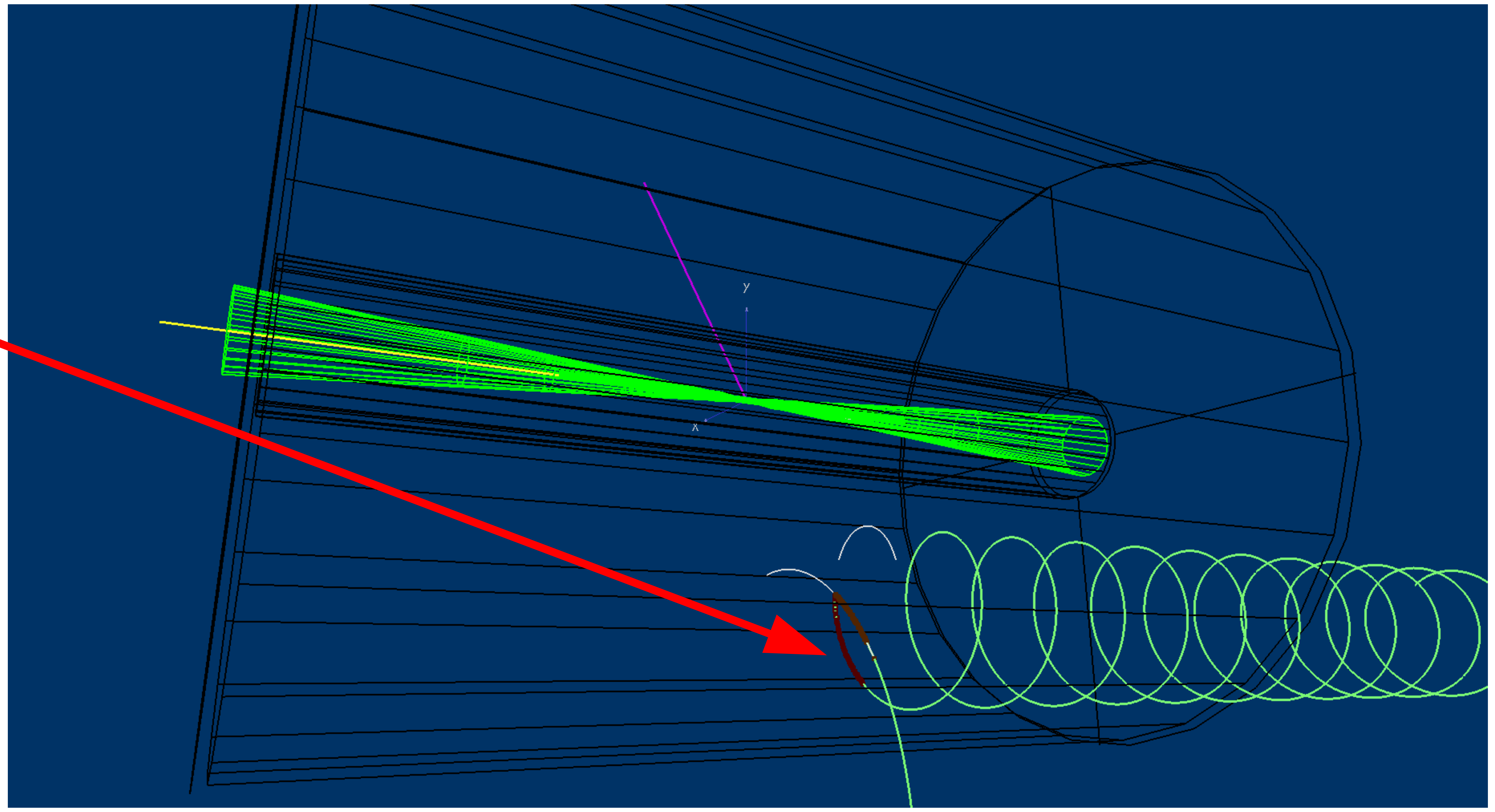


Long-lived, with $c\tau = 1\,\mathrm{m}$

$m_A - m_H = 1, 2, 3, 5\,\mathrm{GeV}$

- Inverted tracks:
- Tracks from very soft particles often reconstructed in the wrong direction
  - Reco as opposite charge particles!!

	Px	Py	Pz
MC:	0.113	-0.339	0.061
Reco:	-0.103	0.344	-0.062



- Solution: if PZ does not point into Z coordinate of the first (last) hit, switch direction of the last (first) hit
  - Improves efficiency by ~ 10%

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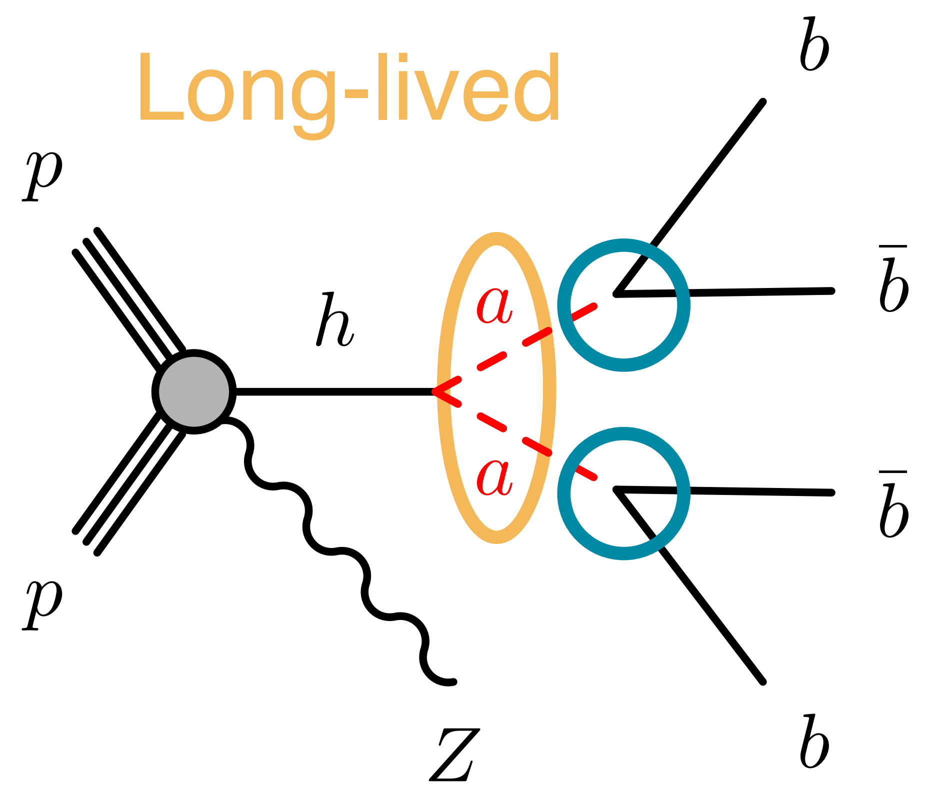
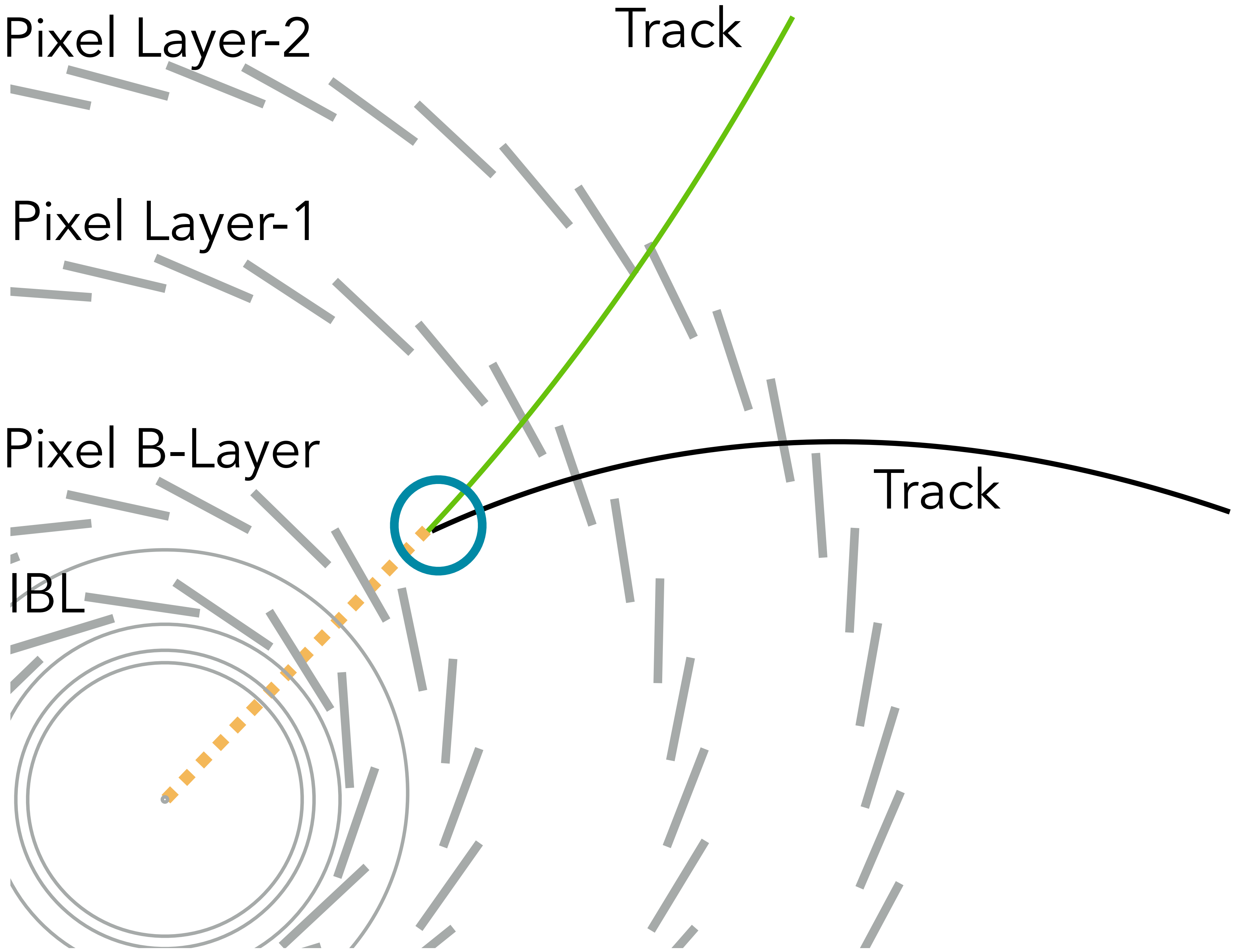
Unconventional tracking

ATLAS

IDTR-2021-03

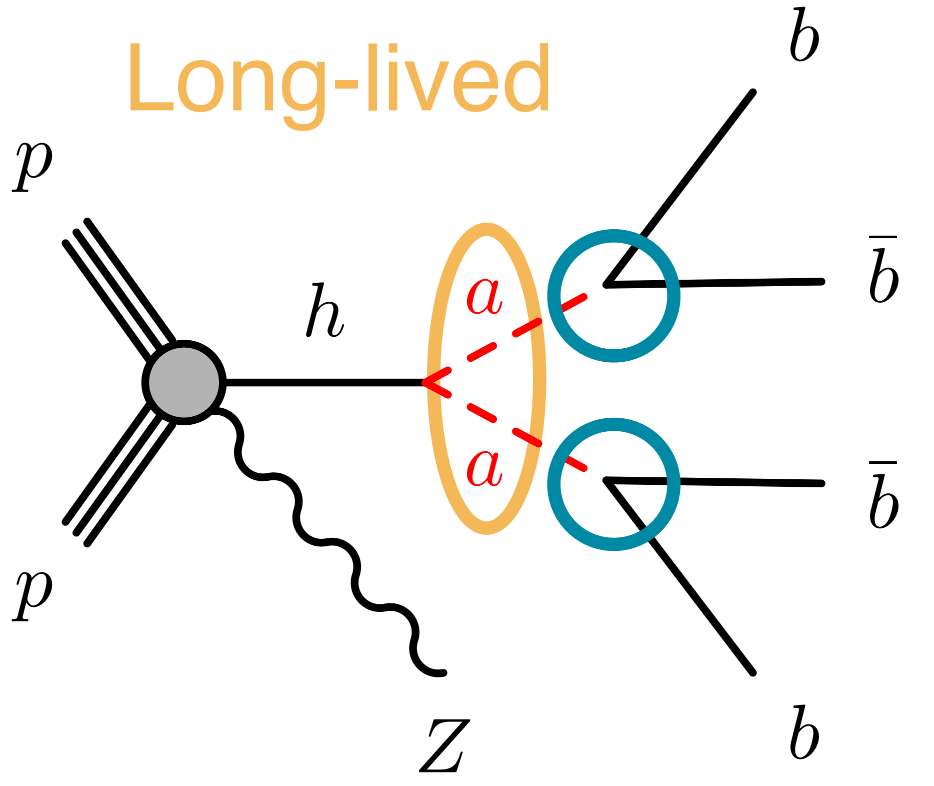


- Standard tracking in ATLAS optimized for prompt particles:
  - point back to the interaction point
  - tight requirements in number of silicon hits and impact parameter
  - would reject tracks from displaced decays



Unconventional tracking

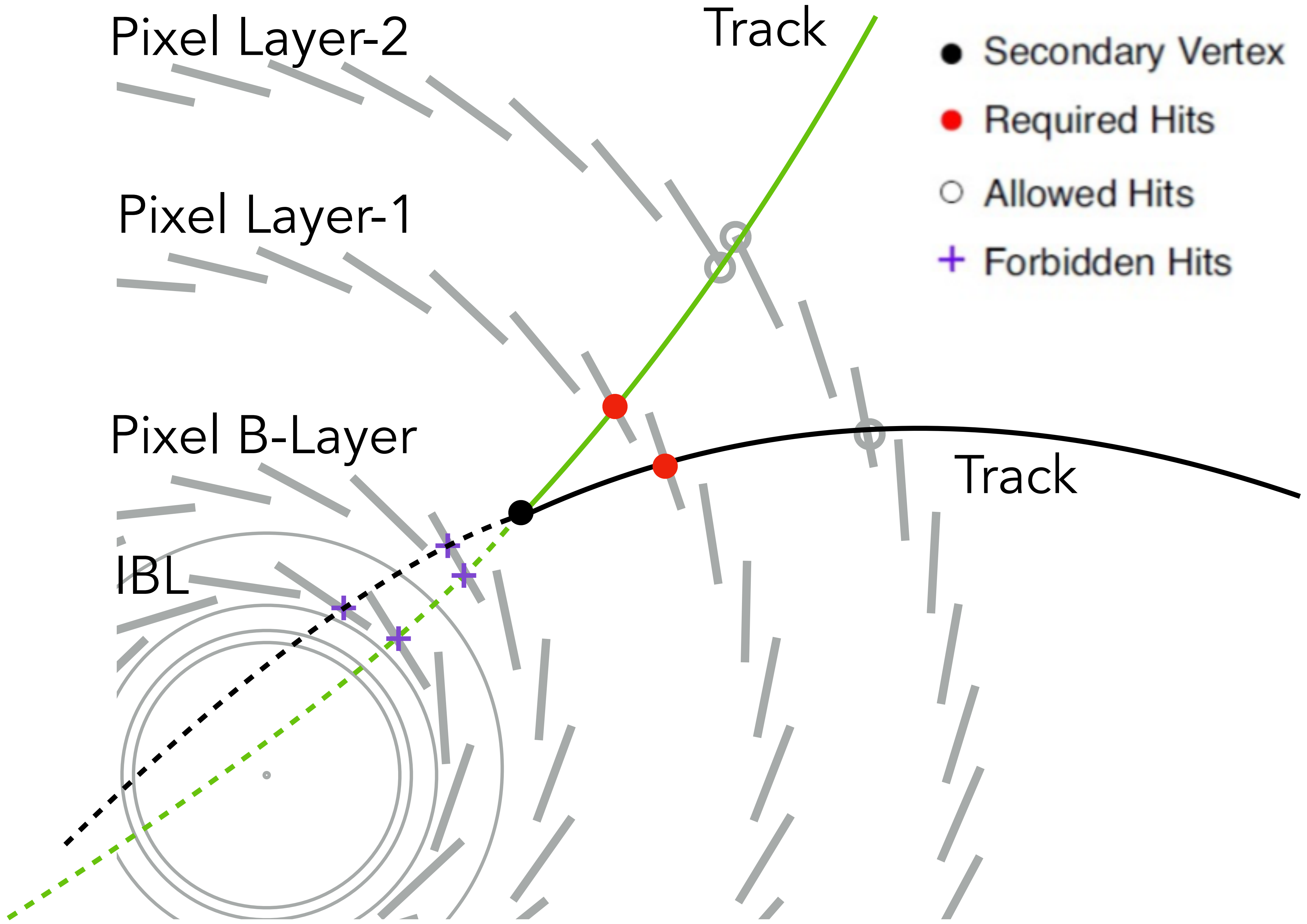
[IDTR-2021-03]



ATLAS

- Standard tracking in ATLAS optimized for prompt particles:
  - point back to the interaction point
  - tight requirements in number of silicon hits and impact parameter
  - would reject tracks from displaced decays

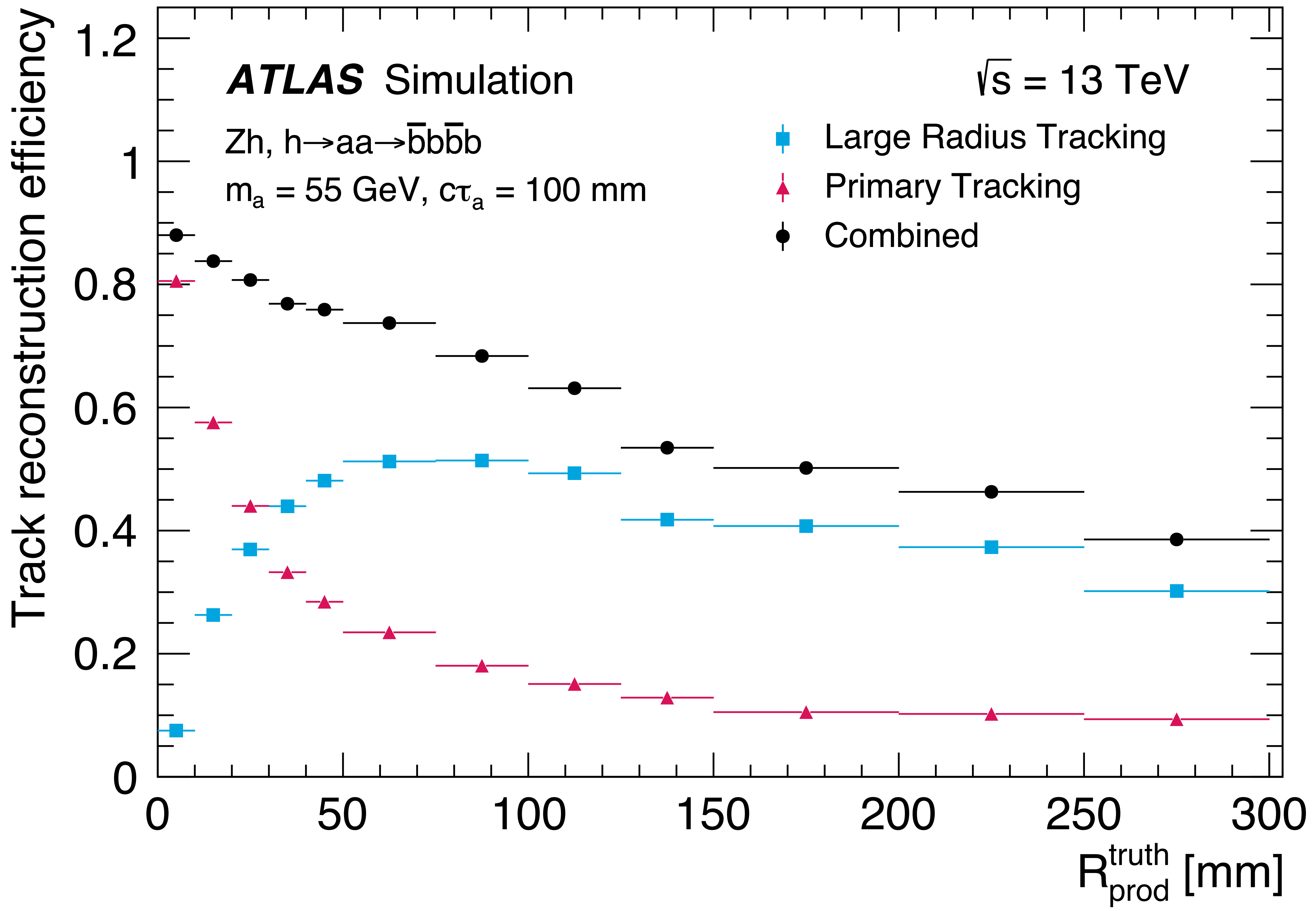
- Large radius tracking (LRT)
  - Re-run with hits not associated with existing tracks
  - Relax requirements in number of silicon hits and d0



Unconventional tracking

ATLAS

- Standard tracking in ATLAS optimized for prompt particles:
  - point back to the interaction point
  - tight requirements in number of silicon hits and impact parameter
  - would reject tracks from displaced decays
- Large radius tracking (LRT)
  - Re-run with hits not associated with existing tracks
  - Relax requirements in number of silicon hits and d0
  - targets tracks with displacements up to 300 mm



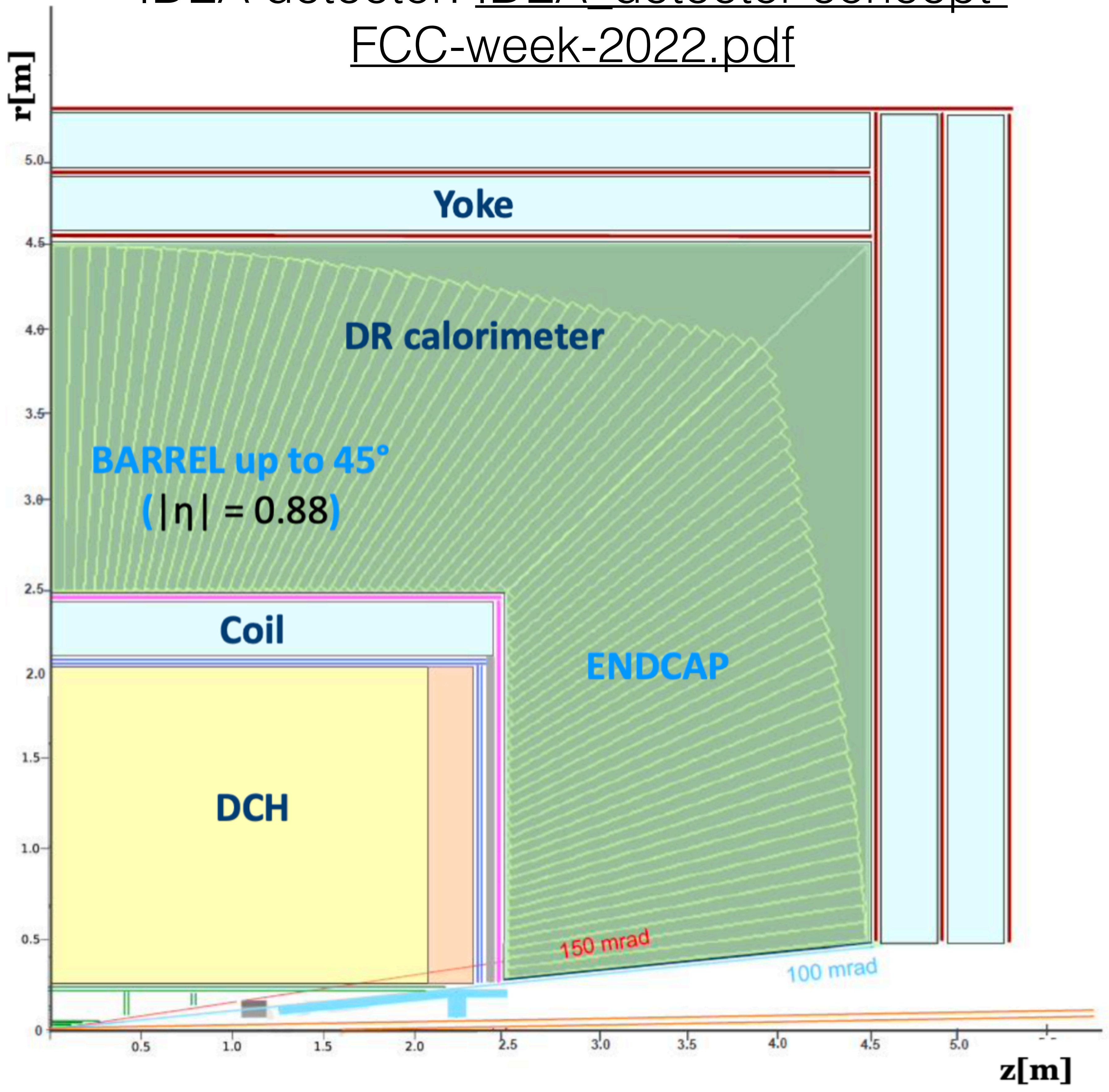
Unconventional tracking

Studies at FCC-ee

- Proposed detector designs for FCC-ee:
  - CLD design
  - IDEA design
  - Noble Liquid ECAL Base design
- Opportunities for new creative detectors, e.g. designed for LLP search such as HECATE (arXiv:2011.01005)

- The IDEA detector is used in this study:
  - Silicon pixel vertex detector
  - Ultralight drift chamber (DCH)
  - Dual readout (DR) calorimeter
- The detector simulation of IDEA is done in DELPHES with a fast parametric simulation

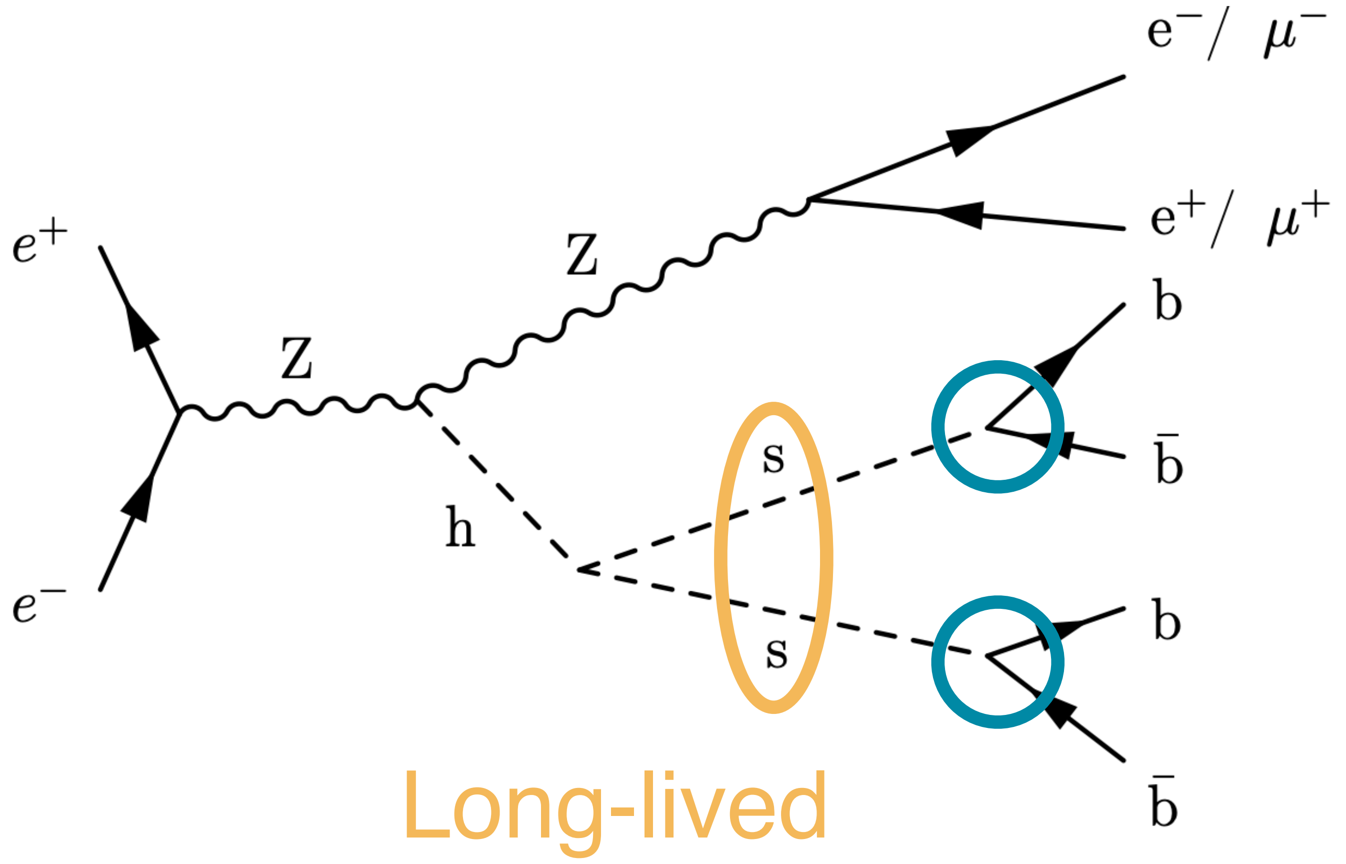
IDEA detector: IDEA_detector-concept-FCC-week-2022.pdf



From Magdalena Vande Voorde, Giulia Ripellino

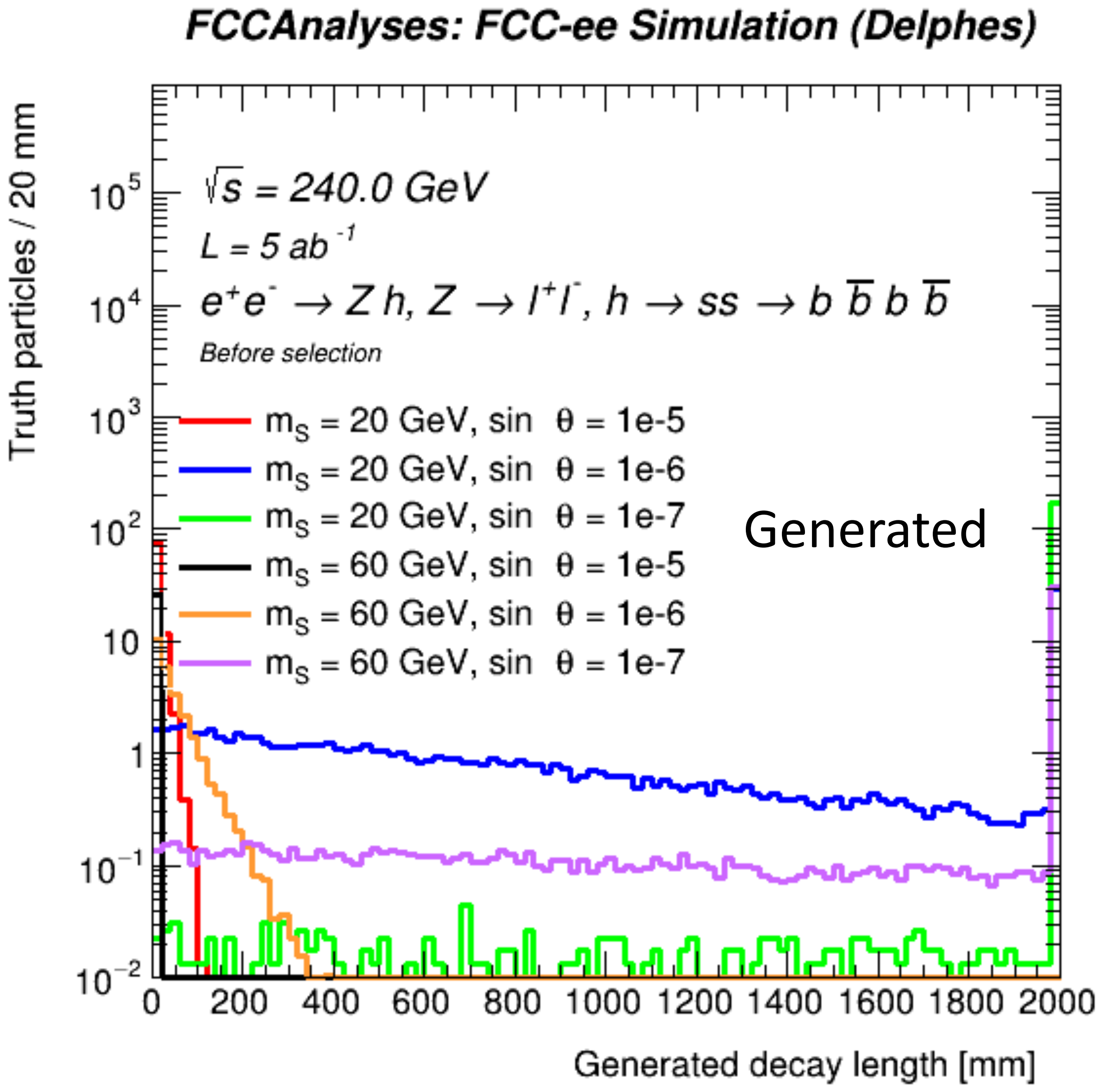
Unconventional tracking

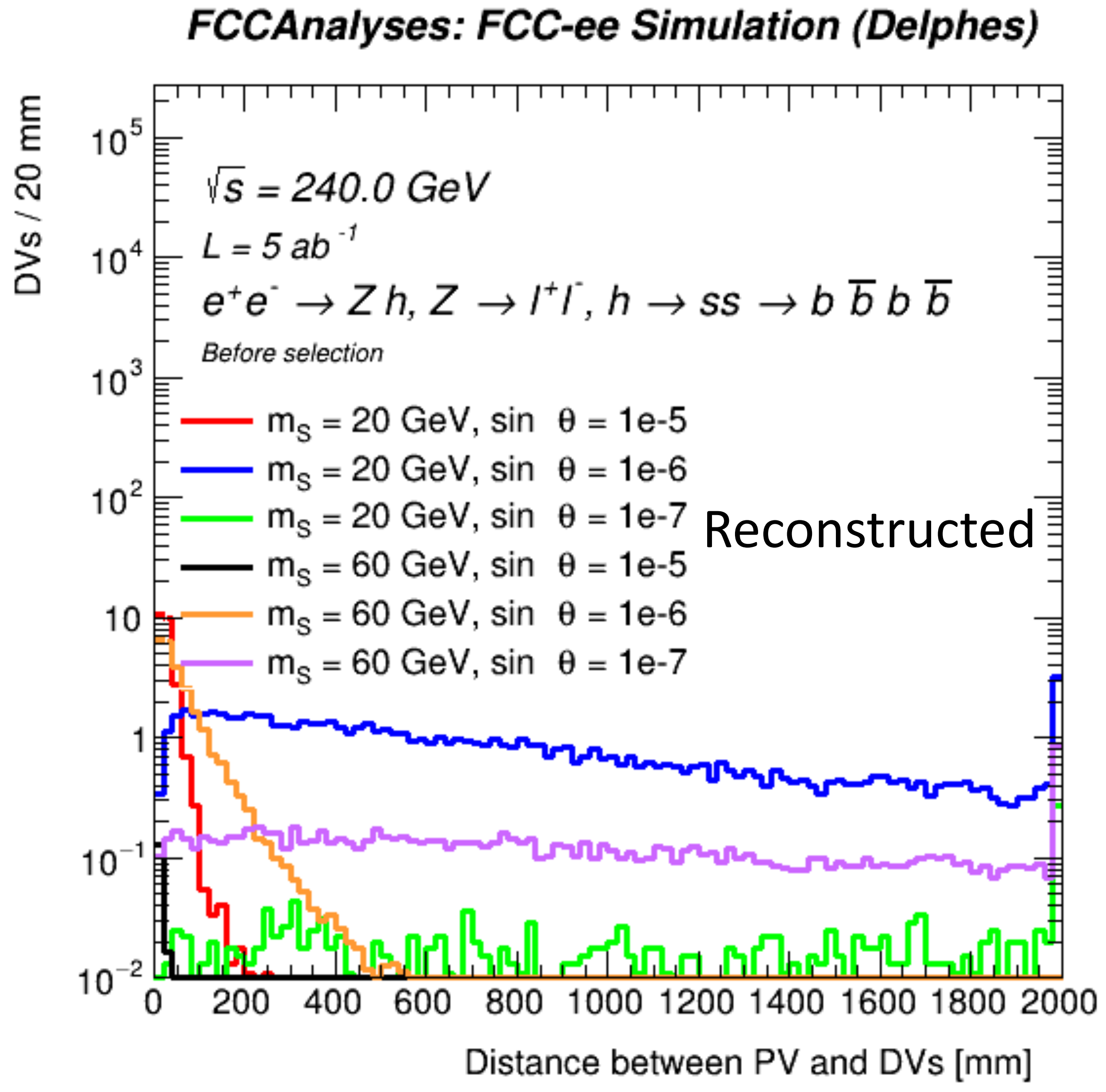
Studies at FCC-ee



- Using current tools in the FCCAnalyses framework adapted to the ZHss model
  - Extra constraints and functions inspired by ATLAS DV reconstruction

- Secondary vertex finder (arXiv:1506.08371)
  - Designed for ILC/CLIC and primarily used for flavour-tagging jets
  - Added track selection: non-primary, pT > 1 GeV and |d0| > 2 mm
  - Added and tested vertex merging (in progress)





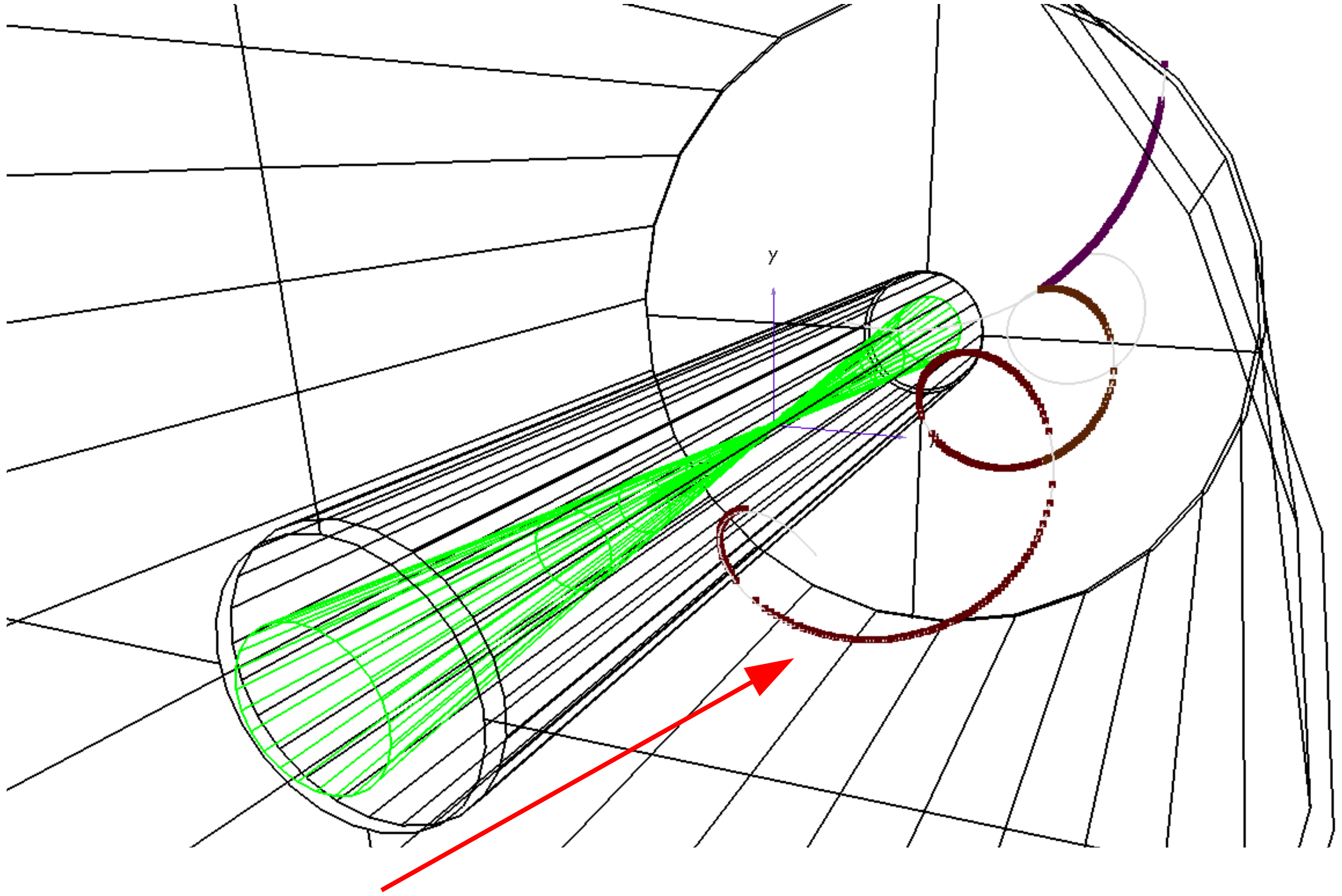
Details in talk at the ECFA WG1-SRCH meeting

From Magdalena Vande Voorde, Giulia Ripellino

Unconventional tracking

Studies at ILD

- Missing hits in TPC
- Single track can often be reconstructed as several tracks
- Becomes more important if we look for **vertices far from the IP**



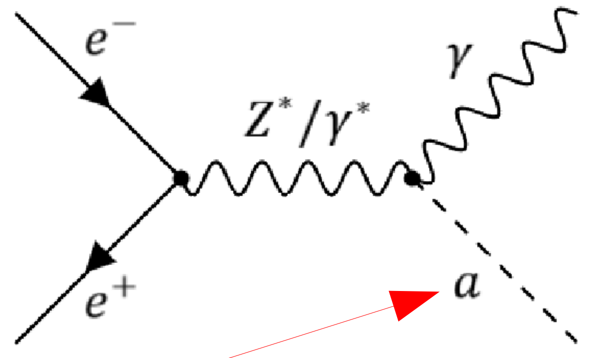
This track was reconstructed as two separate ones, with very distante reference points

From Jan Klamka

Unconventional tracking

Studies at ILD

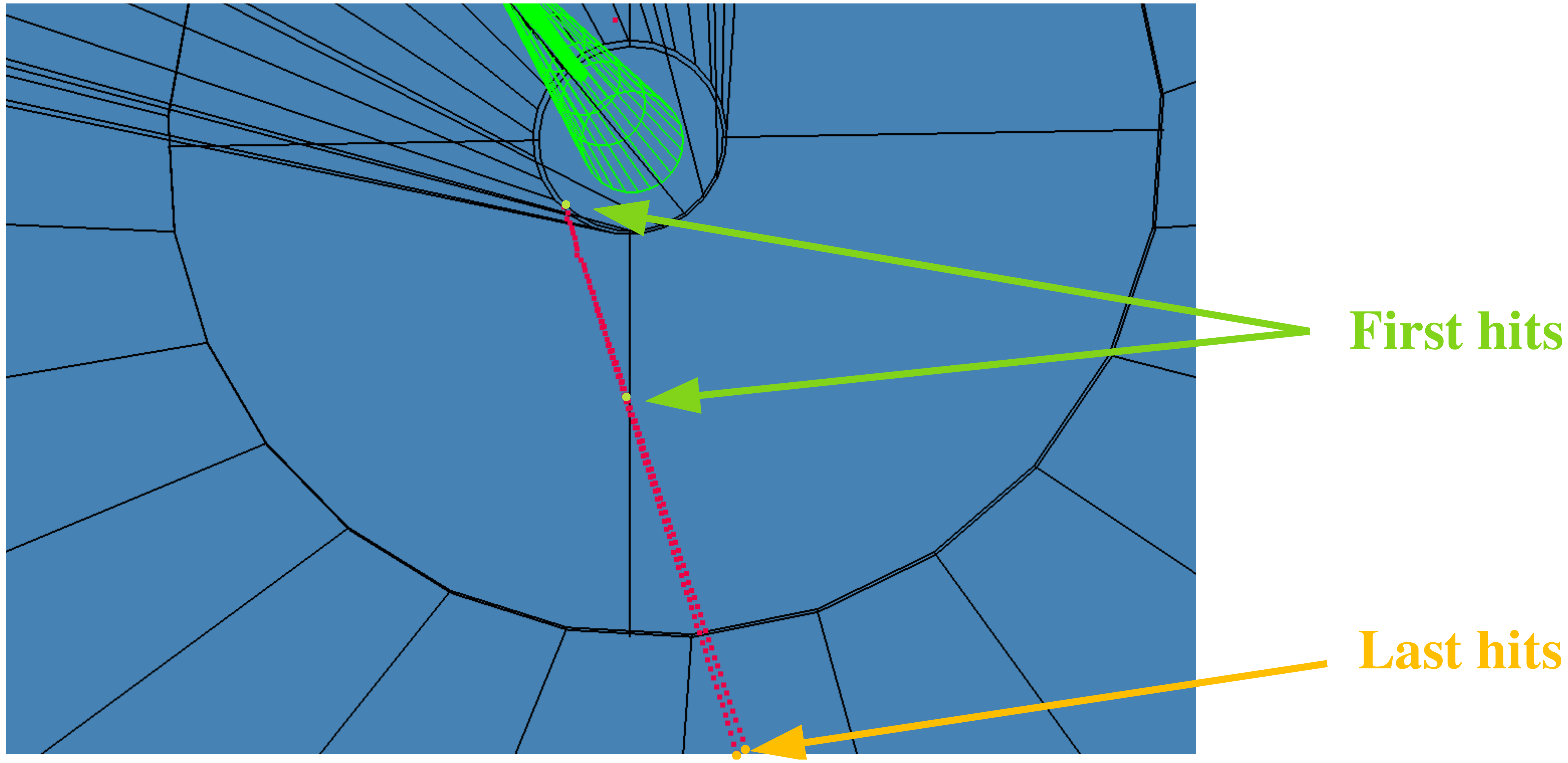
The opposite extreme case, (large boost, high-pT final state)
→ (tuned) axion-like particle model sample



Long-lived, $c\tau = 10\,\mathrm{mm}$
$m_a = 0.3, 1, 3, 10\,\mathrm{GeV}$

- Collinear tracks in TPC (ALPs)
- Impossible to distinguish the tracks close to the production vertex

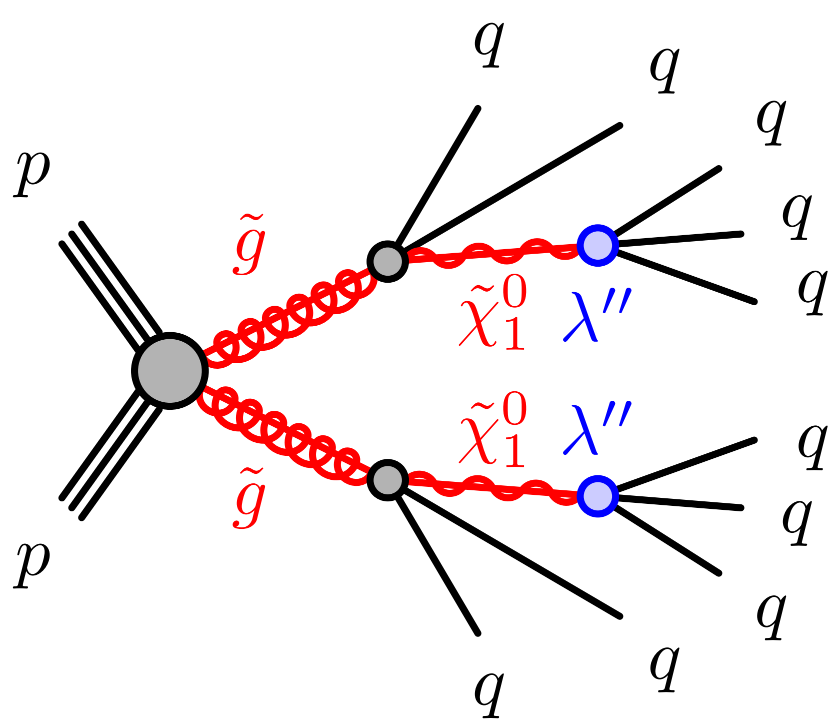
- Tracking often assigns first hit of the second track far from the vertex (Small influence on reco. momentum)
- Need to carefully evaluate the hits distribution



From Jan Klamka

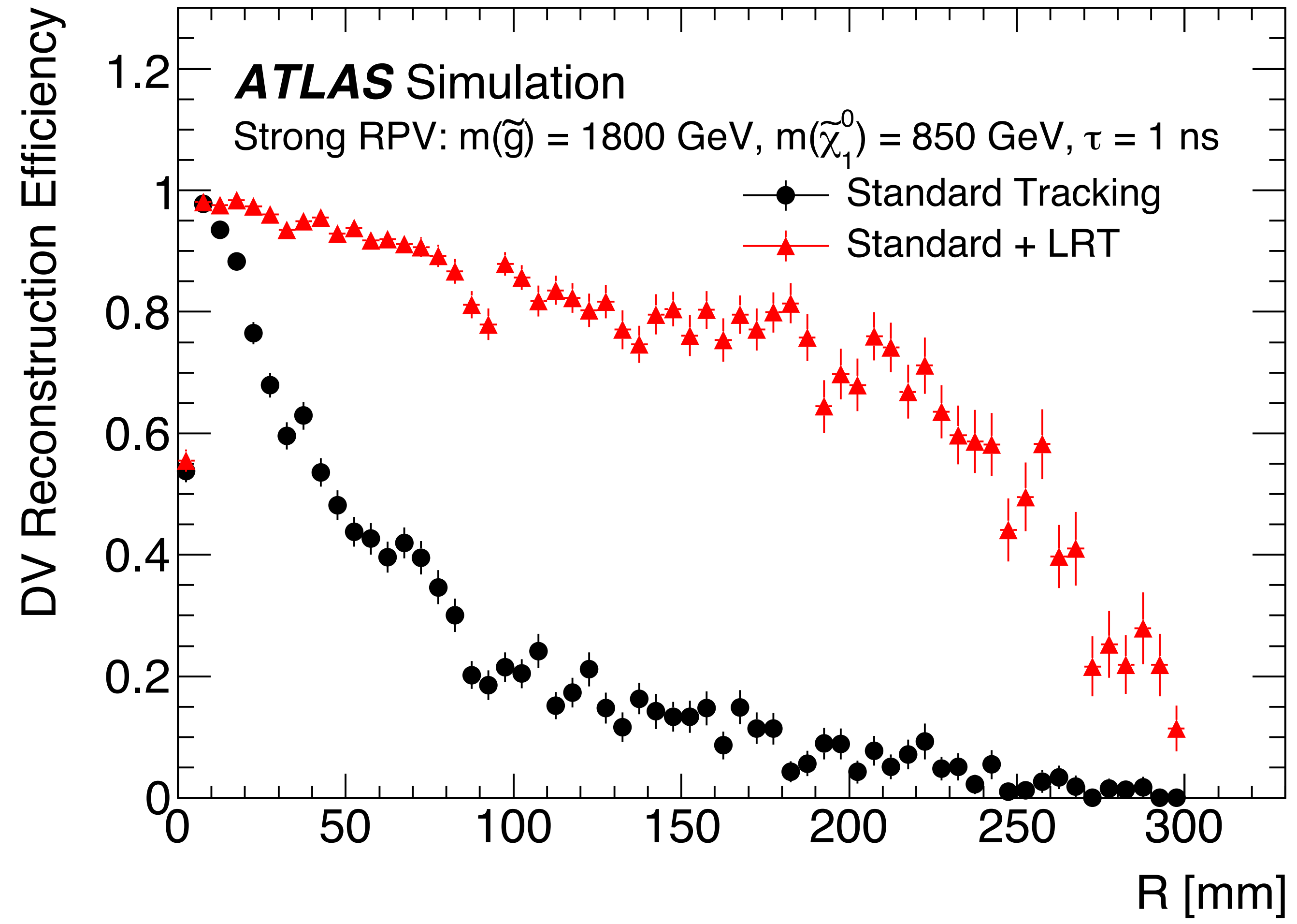
Full analysis using Displaced vertices

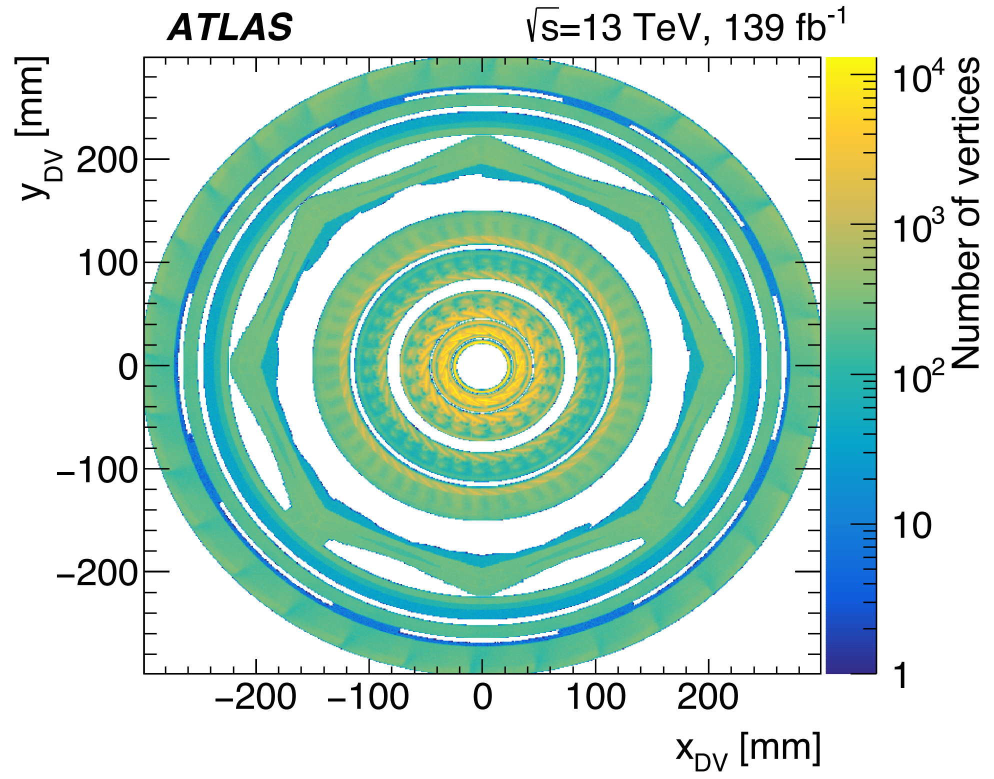
SUSY-2018-13



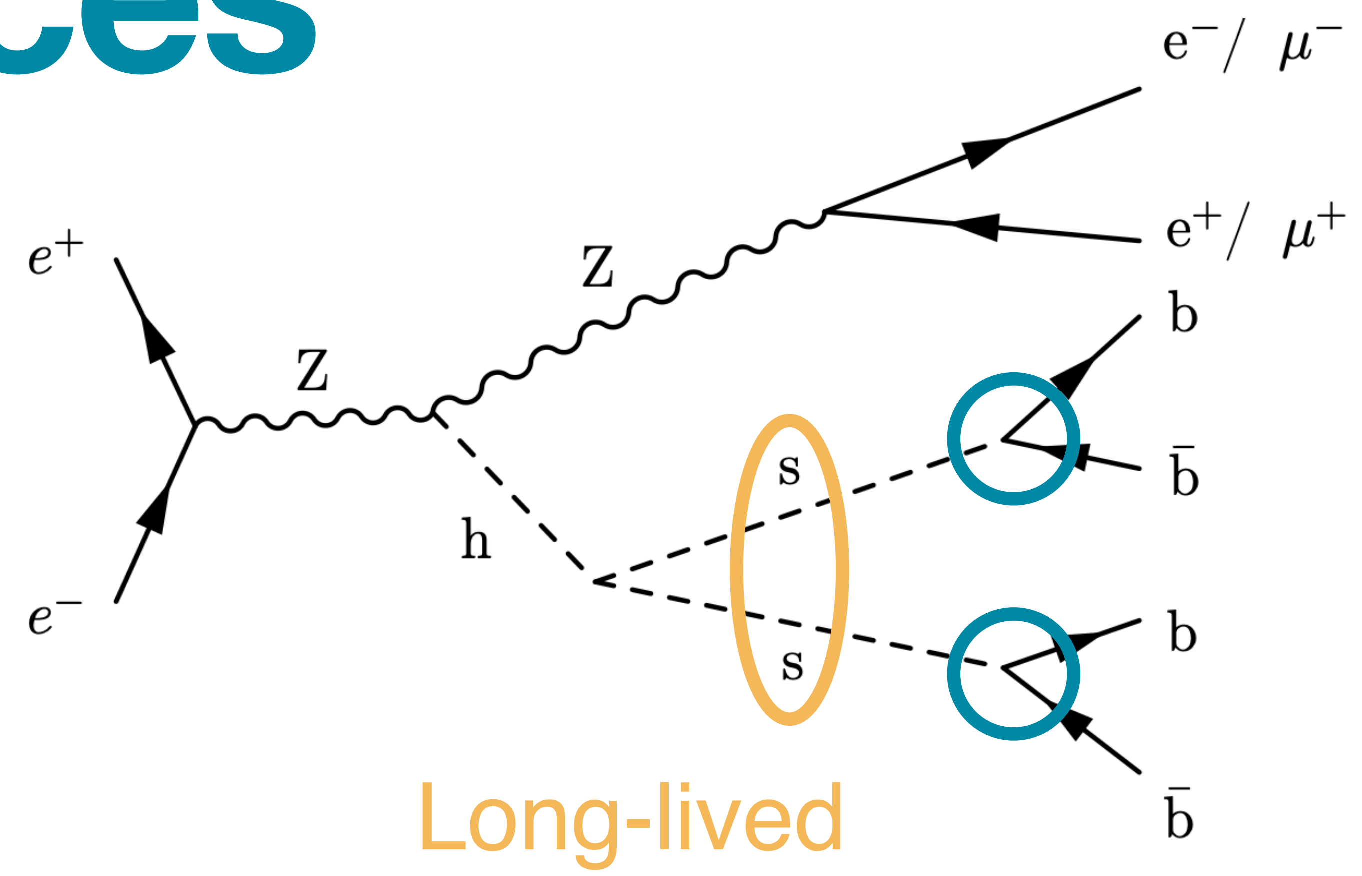
ATLAS

- Long-lived particles decaying into hadrons in the ATLAS inner detector
- SM (MSSM) R-parity-violating (RPV)
  - mean proper lifetimes τ up to $O(10)$ ns
- Using LRT in events with multiple energetic jets and a displaced vertex
- Three main sources of background:
  - hadronic interactions: detector material
  - accidental crossings: low-mass displaced vertices crossed by an unrelated track
  - merged vertices: close-by low-mass displaced vertices
- Reject them with DV selection:
  - DV at least 4 mm away from any collision vertex
  - DVs must satisfy a material map veto
  - DVs must have at least five tracks
  - mDV > 10 GeV
- Reach ~zero background analysis





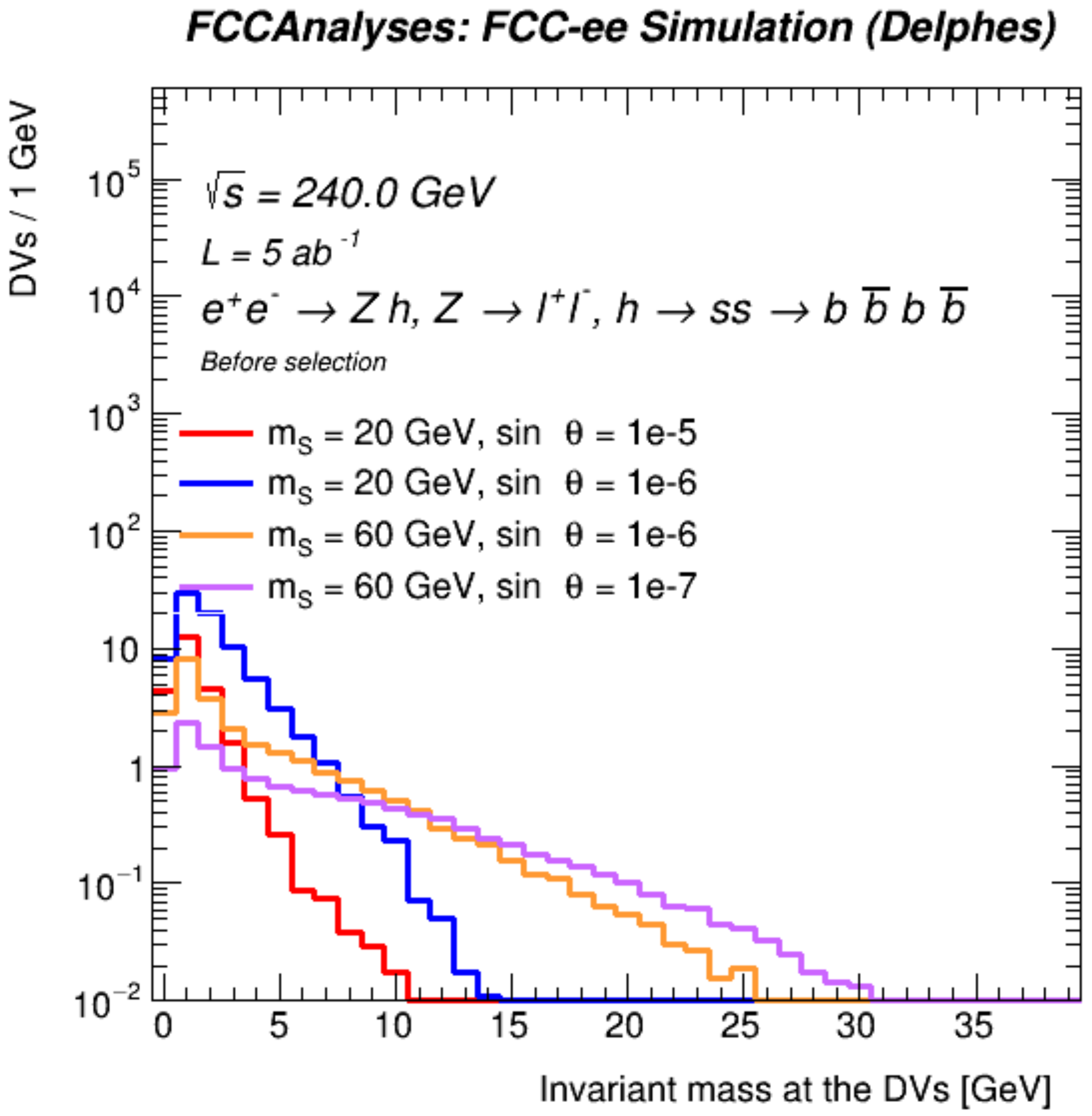
Full analysis using Displaced vertices



Studies at FCC-ee

- Preliminary vertex selection:
  - Distance of DV from PV required to be
    - in the tracker volumen
    - outside the innermost region to exclude heavy-flavour decays
  - Charged invariant mass at DV: to remove background DVs

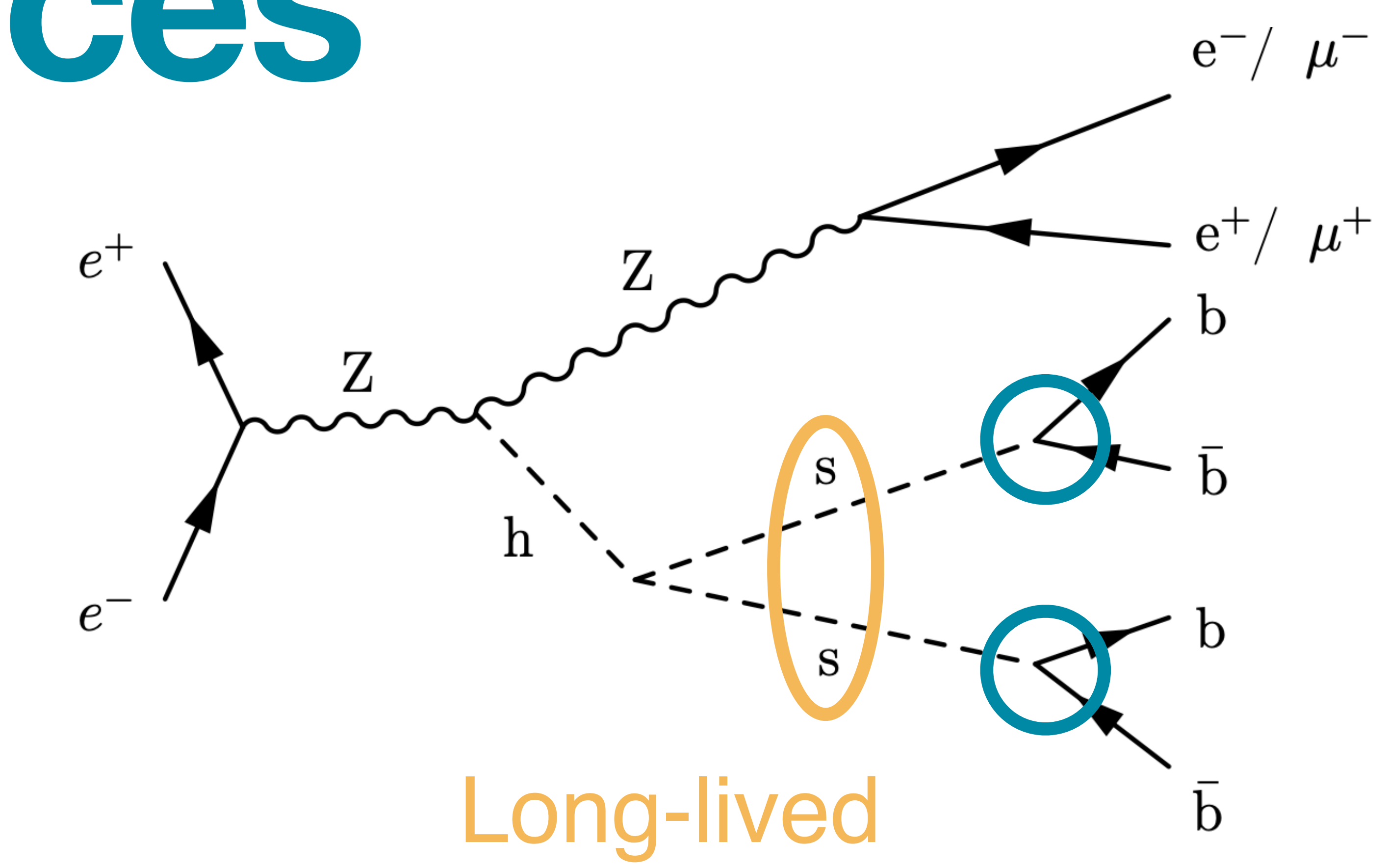
Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\|d_0\|$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV



Visible/charged invariant mass at the DVs

From Magdalena Vande Voorde, Giulia Ripellino

Full analysis using Displaced vertices

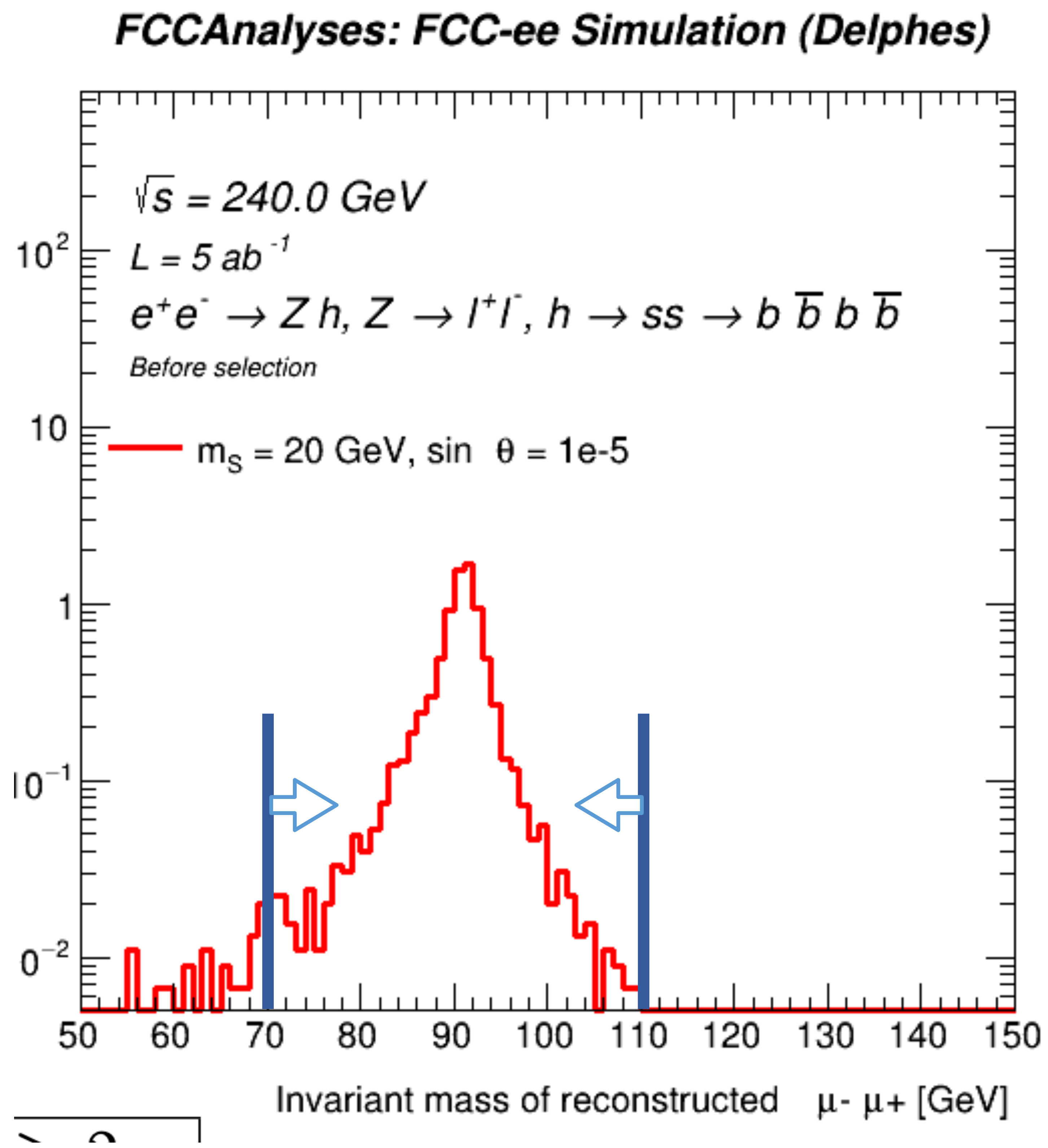


Studies at FCC-ee

- First steps for a sensitivity study
  - Z Pre-selection: 2 SFOS leptons with invariant mass 70 < mll < 110 GeV
  - At least 2 reconstructed DV

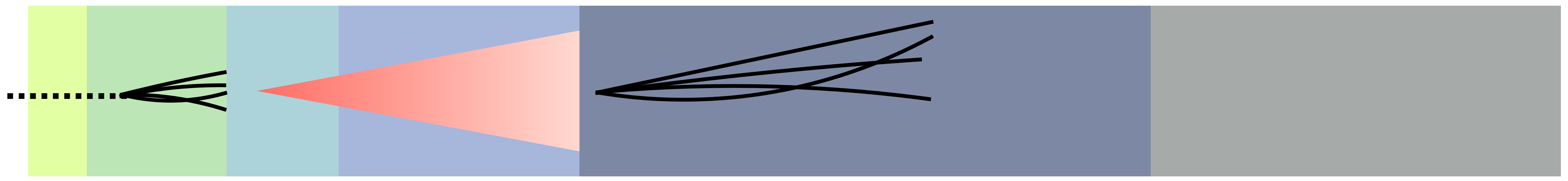
  - Given zero-background, signal points with at least 3 expected events can be excluded to 95% CL

  - Potential sensitivity for all signal samples except for the shortest and longest lifetime samples!



From Magdalena Vande Voorde, Giulia Ripellino

Displaced jets in ATLAS - complementarity

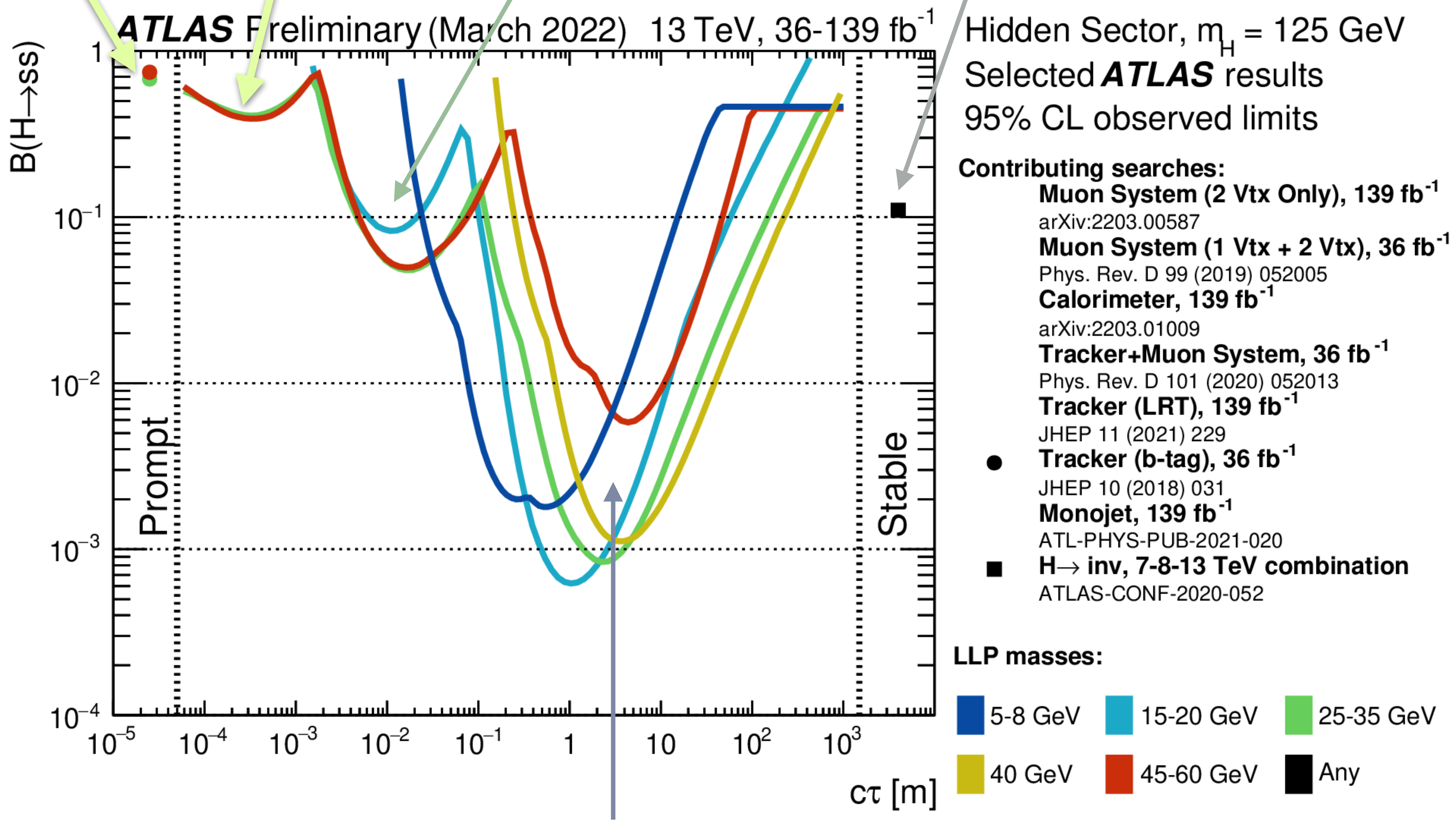


Prompt search reinterpretation

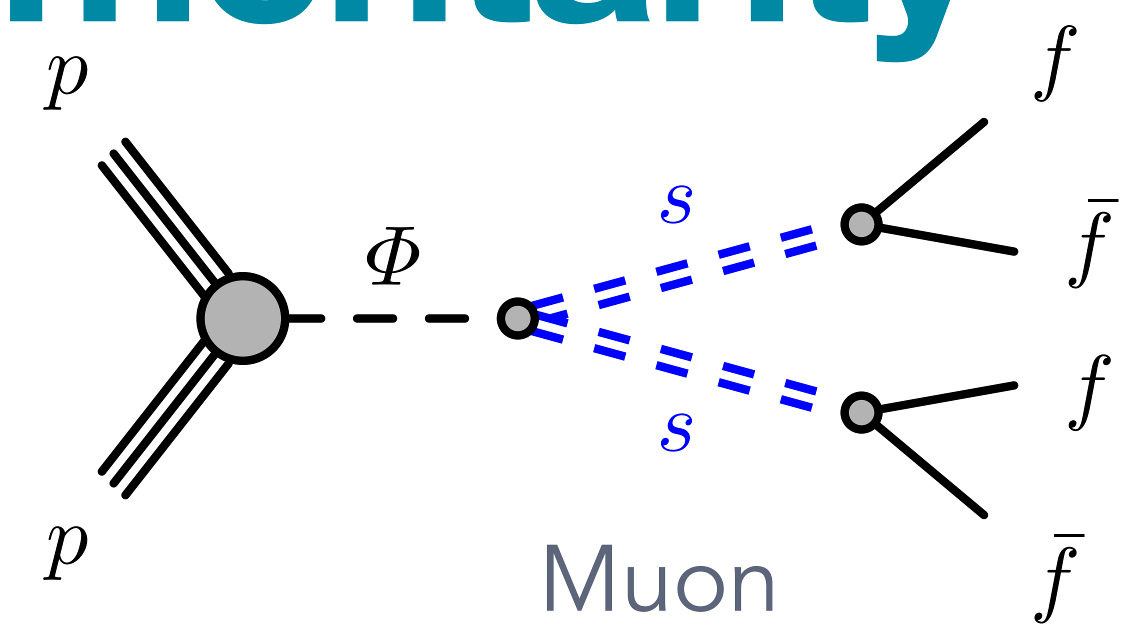
Prompt search

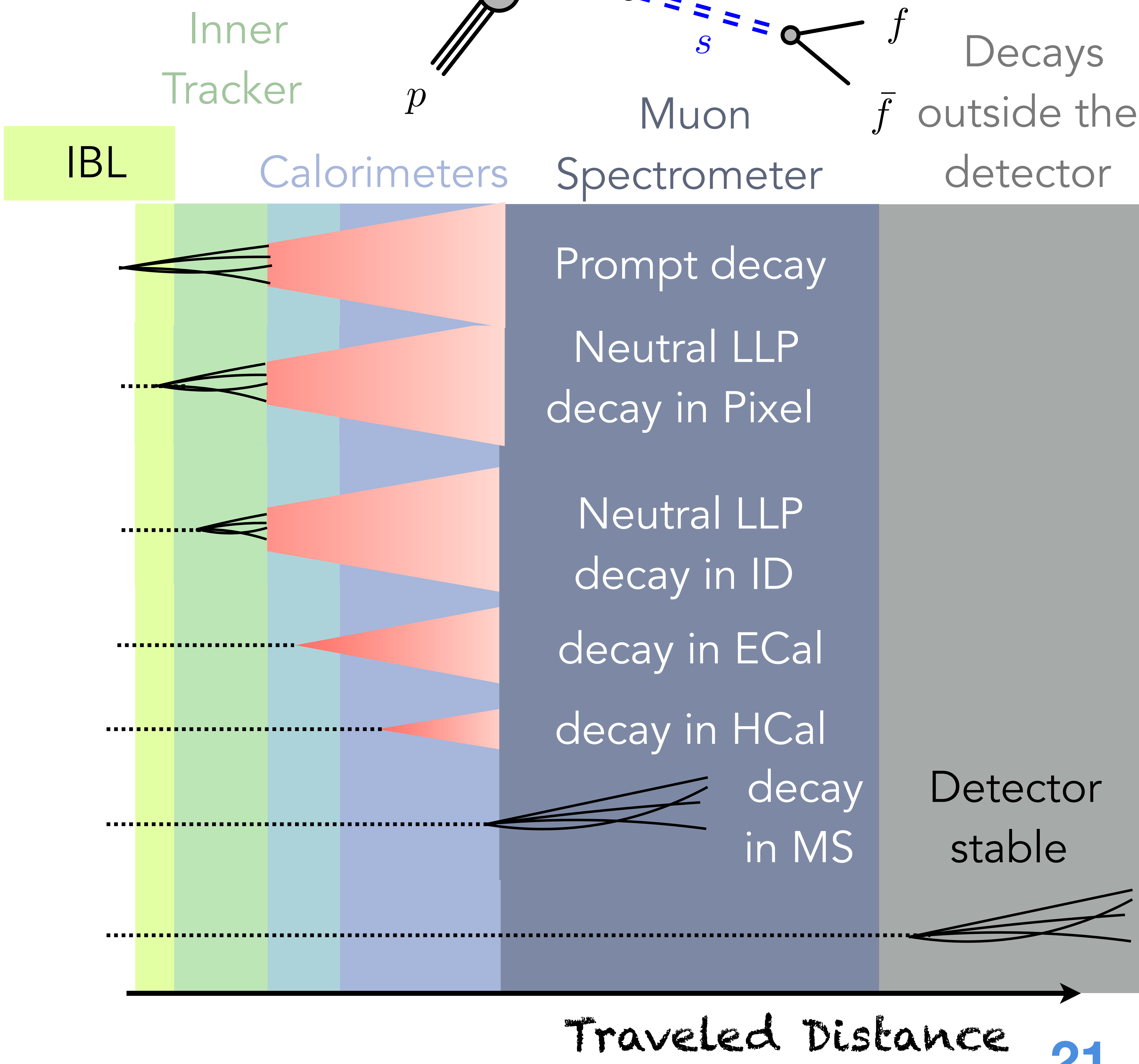
DV based search using LRT

MET-based searches



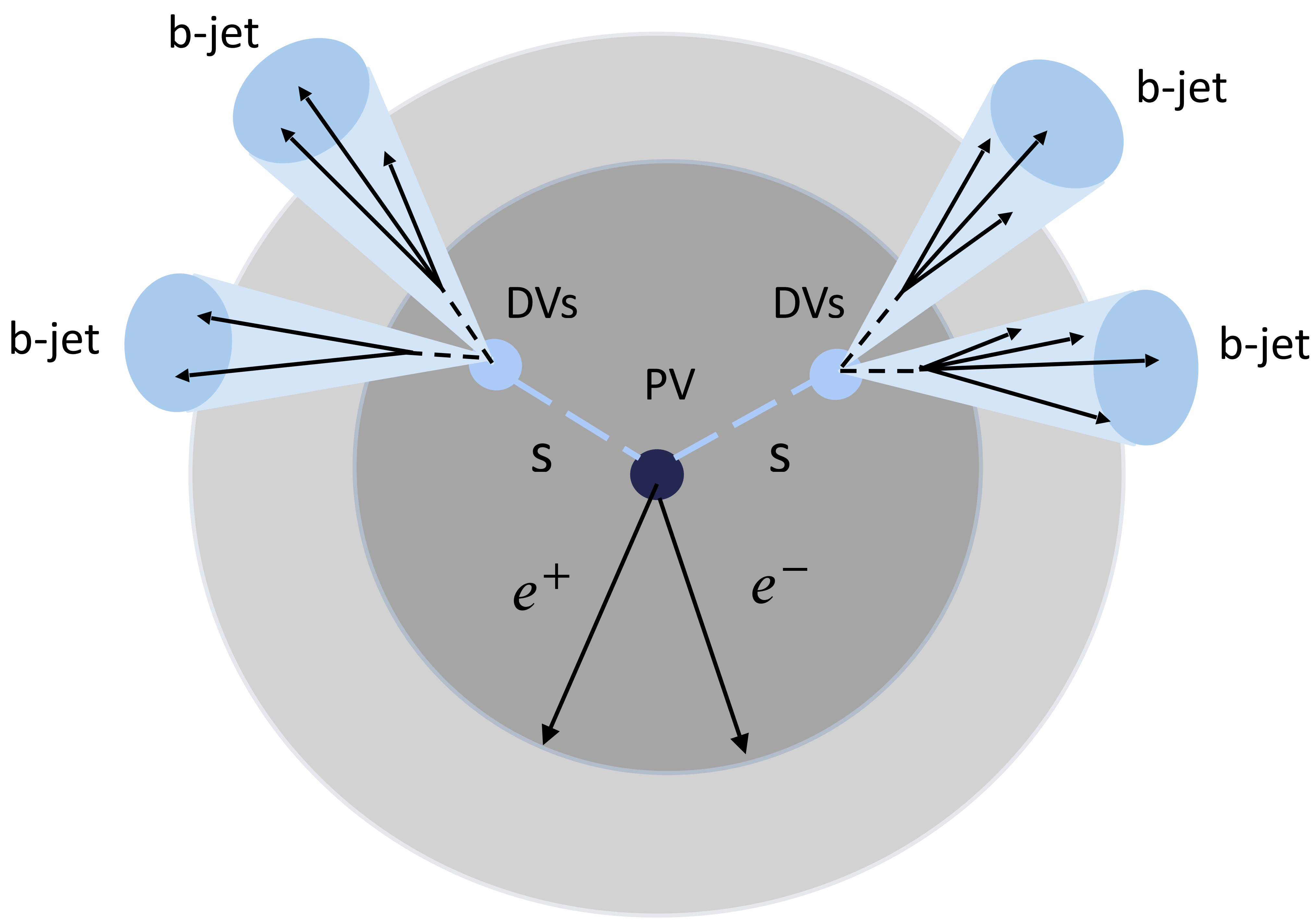
Calo/MS displaced objects searches





Conclusions

- LLPs might be the key for finding BSM physics and they are gaining interest!
- Great effort at the LHC experiments to search for LLPs… BUT! still some signatures to be exploited!
- Future colliders offer a great opportunity to innovate and plan for new unconventional searches
  - Development of new tools and strategies to improve identification of LLPs,
  - Planning for a detector with LLP reconstruction capacities from the beginning
- Lots of effort ongoing, a lot more to come



Backup

IDEA detector layout

Beam pipe: R~1.5 cm

Vertex:

5 MAPS layers

R = 1.7-34 cm

Drift Chamber: 112 layers

4 m long, R = 35-200 cm

Outer Silicon wrapper:

Si strips

Superconducting solenoid coil:

2 T, R ~ 2.1-2.4 m

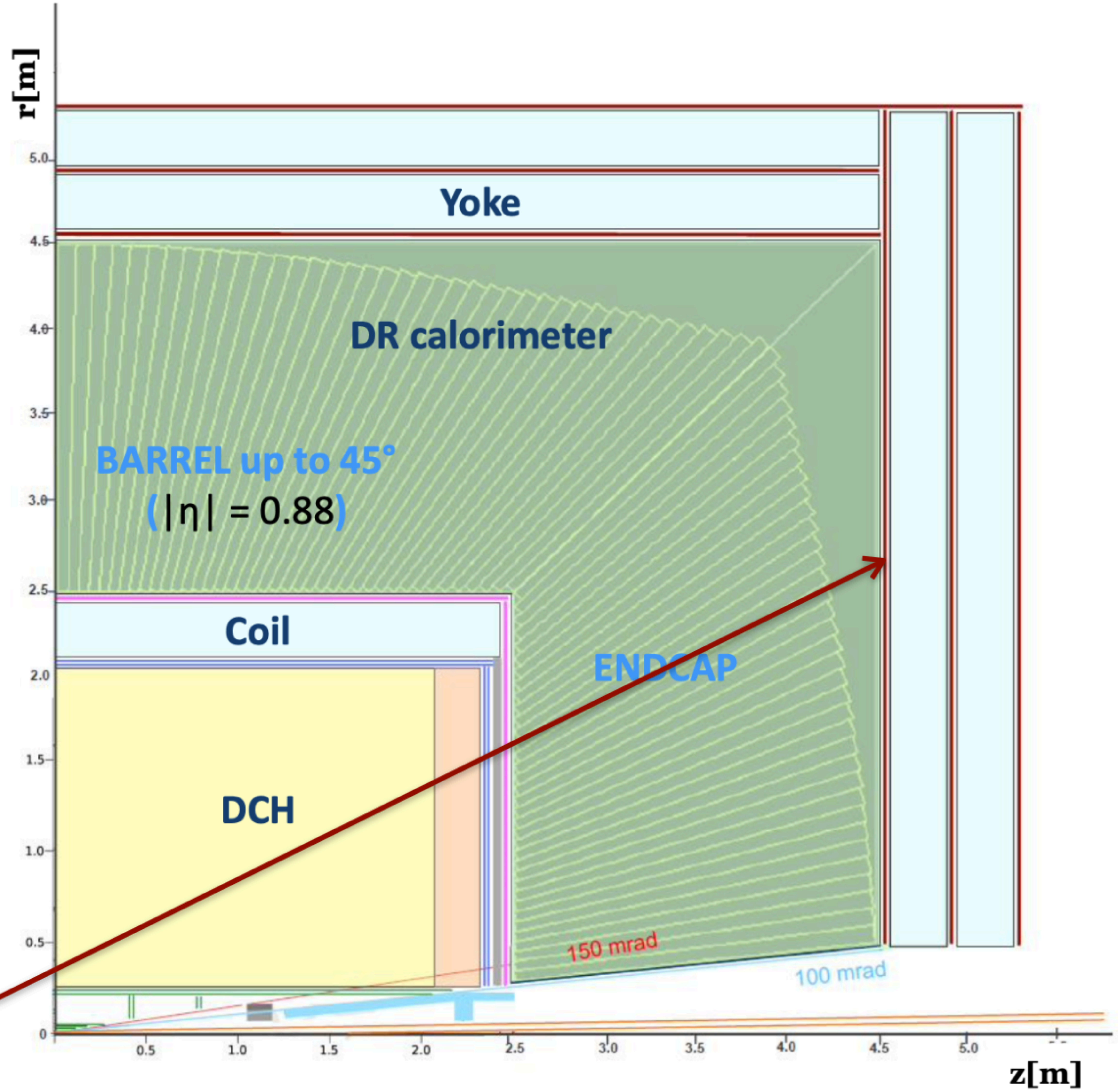
0.74 X_0, 0.16 λ @ 90°

Preshower: ~1 X_0

Dual-Readout Calorimeter:

2m / 7 λ_{int}

Yoke + Muon chambers

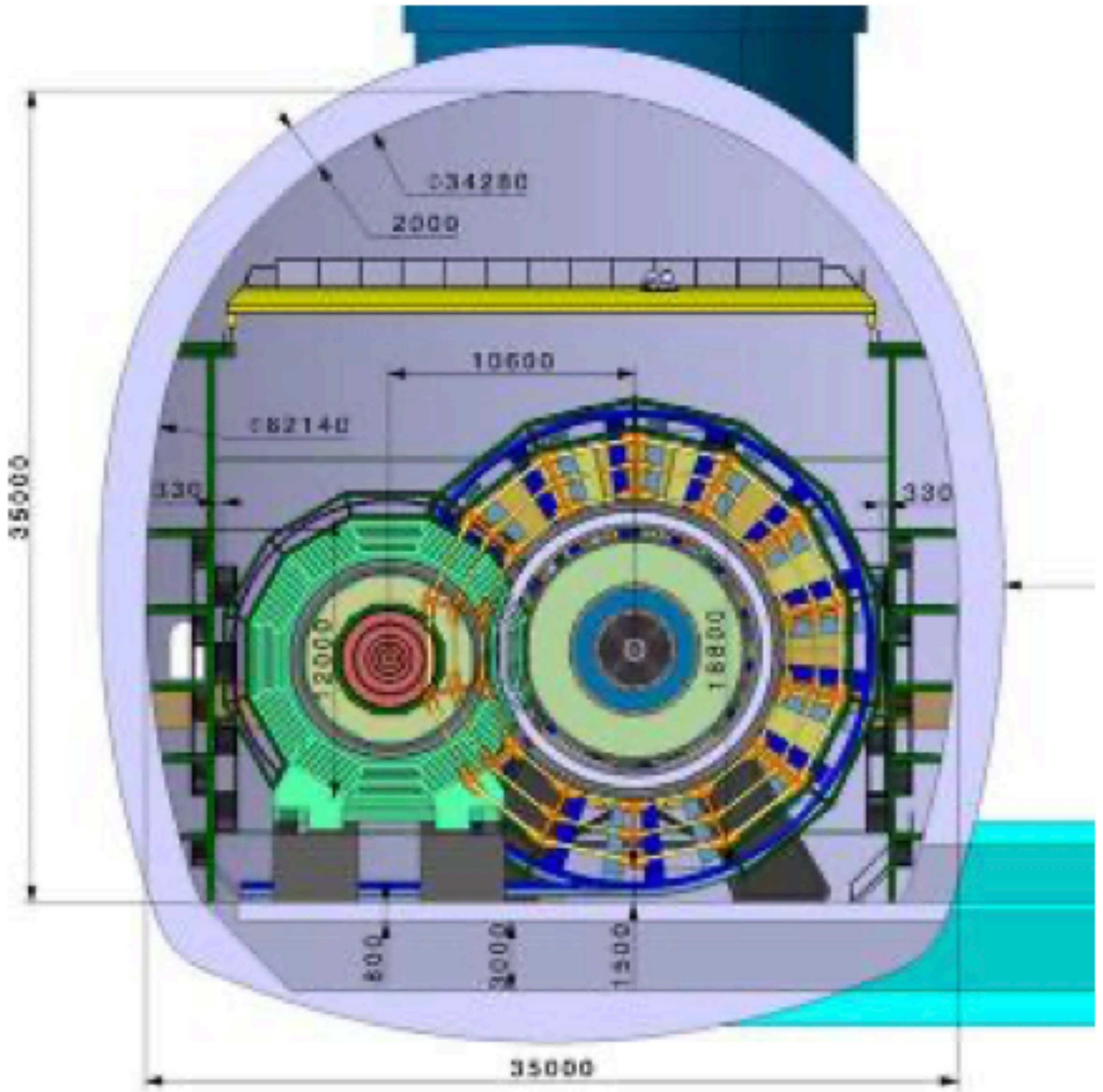


LLPs @ FCC-hh, FCC-ee

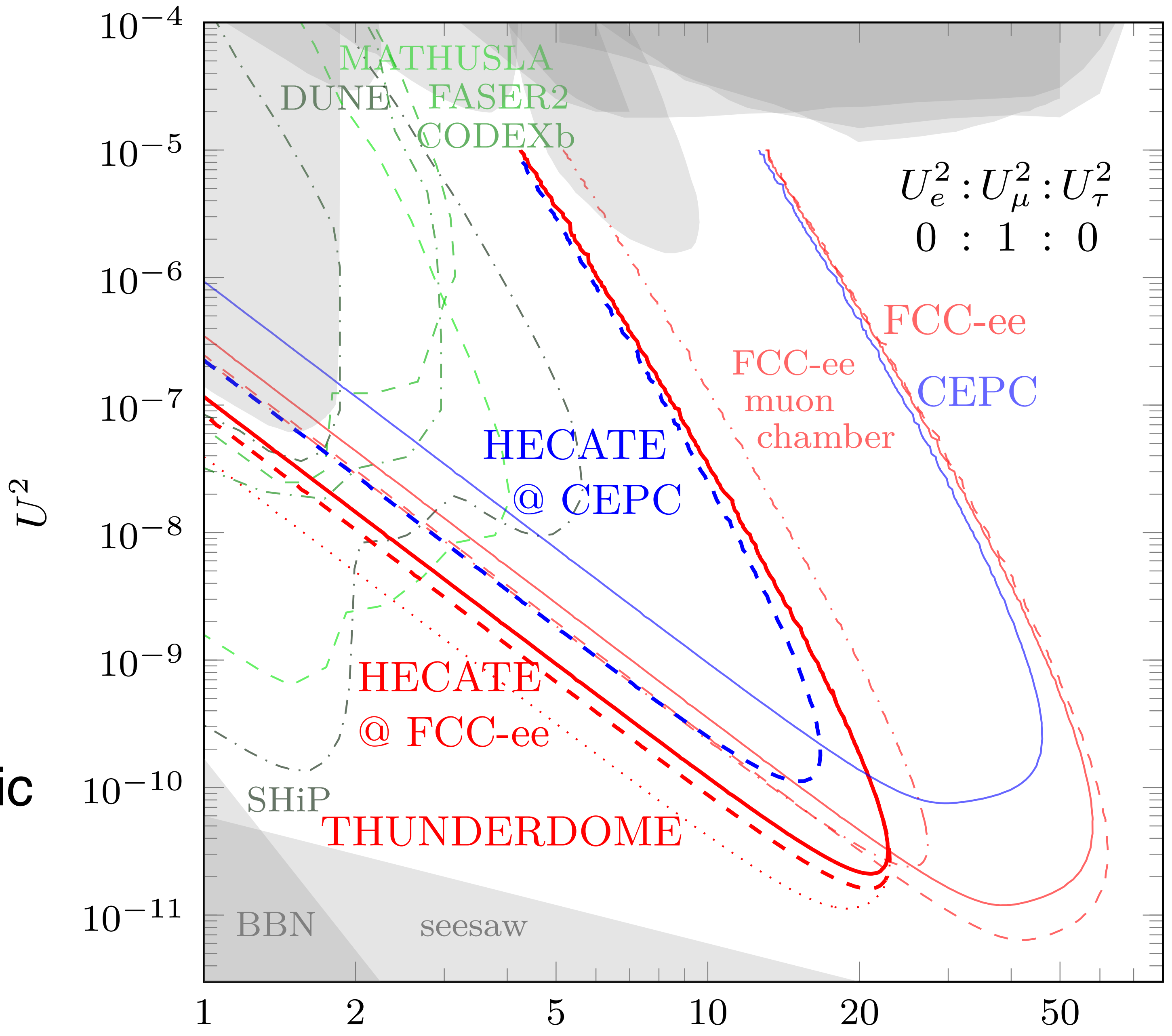
Proposal: 2011.01005

HECATE: HErmetic CAvern TrackER. A long-lived particle detector concept for FCC-ee or CEPC

- For FCC-hh / FCC-ee, main detector will be relatively smaller than the cavern
- Cover detector cavern walls with scintillator plates or RPCs
  - >= 2 layers of 1 m^2 separated by a sizeable distance — timing
  - >= 4 layers for good tracking
  - 4π coverage LLP detector
- FCC main detector as active veto
- Sensitive to a unique area of phase space



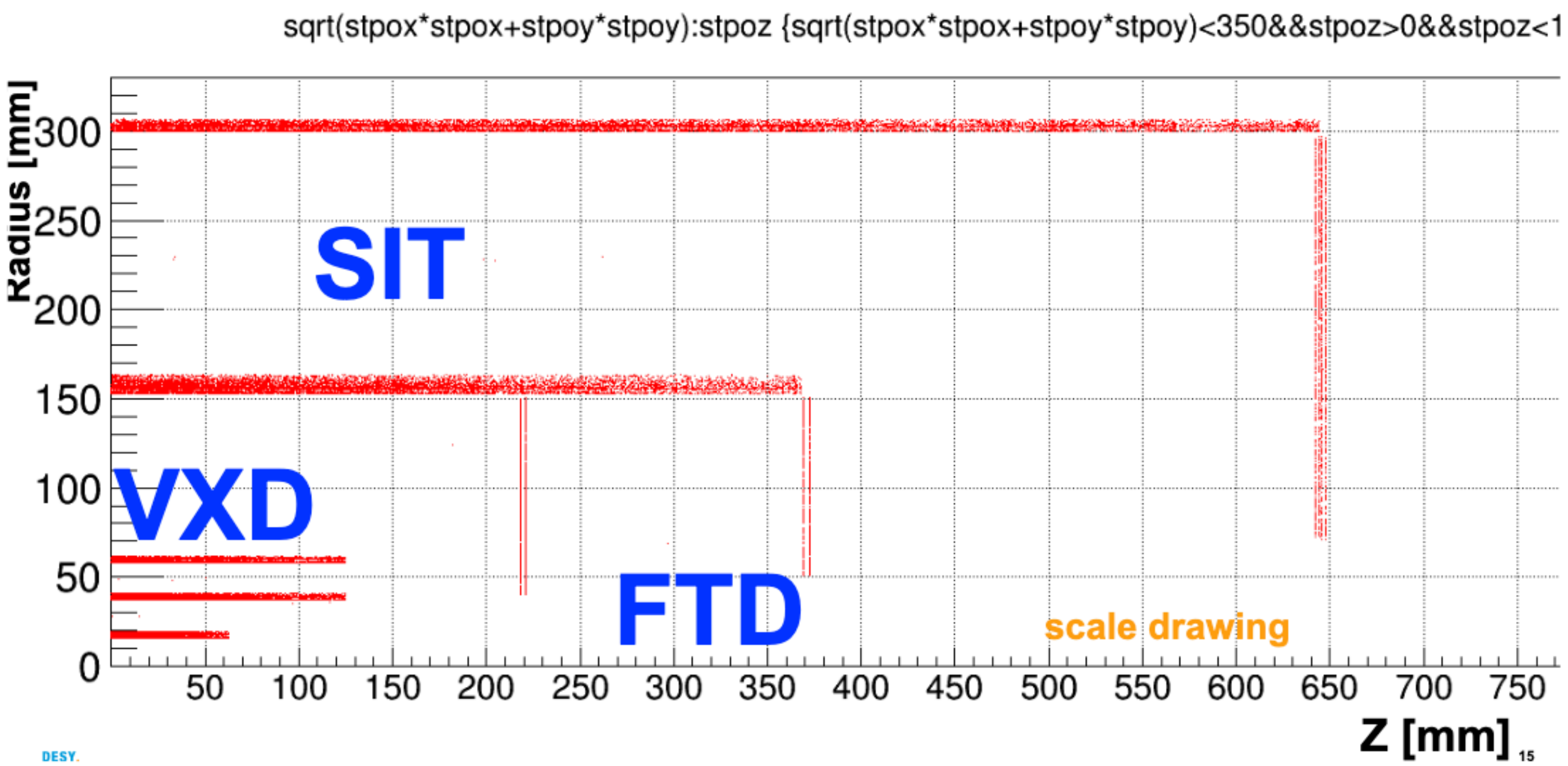
- Cavern size: r~15 m and z~50 m
- Main detector size =(10m)

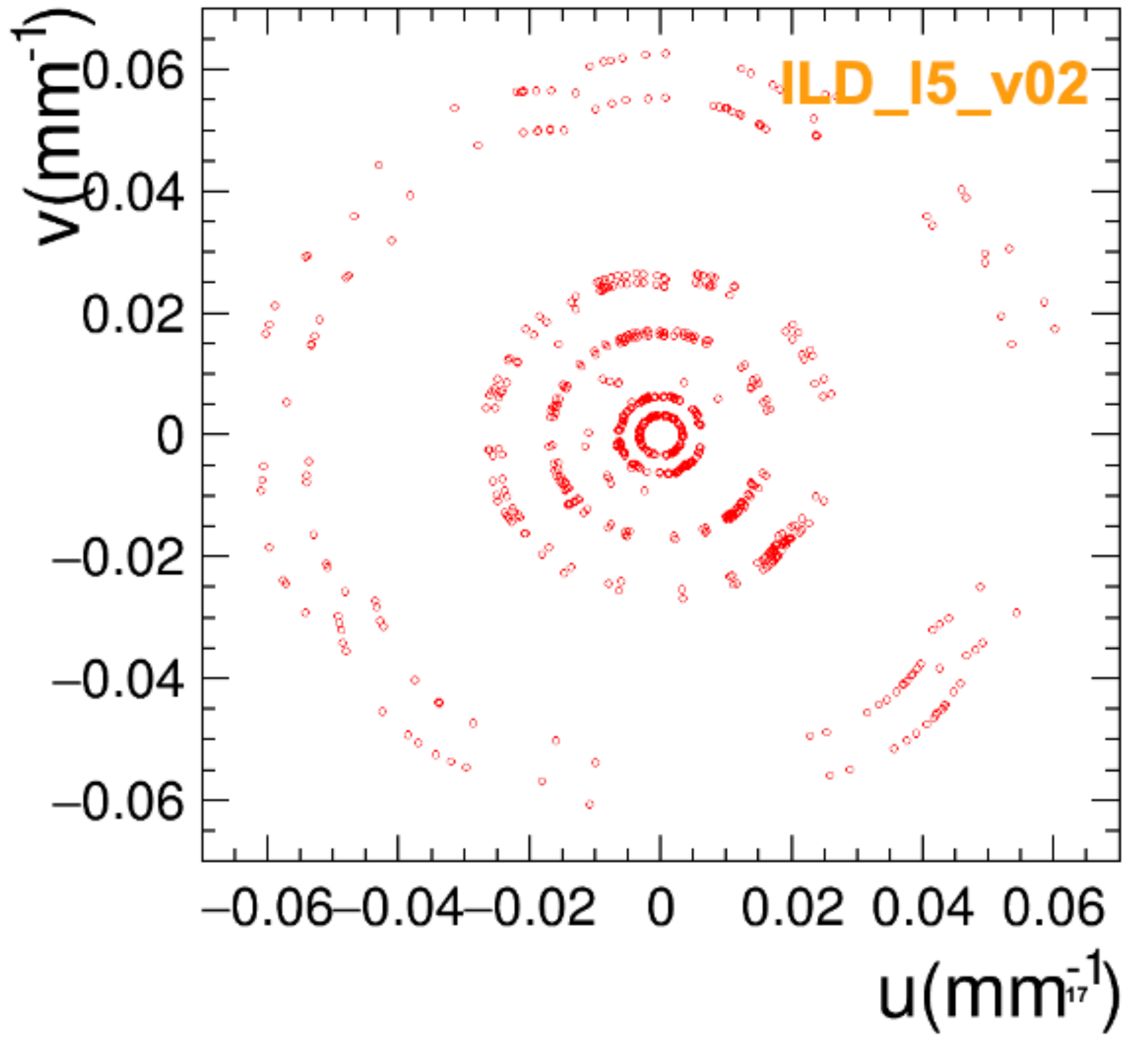


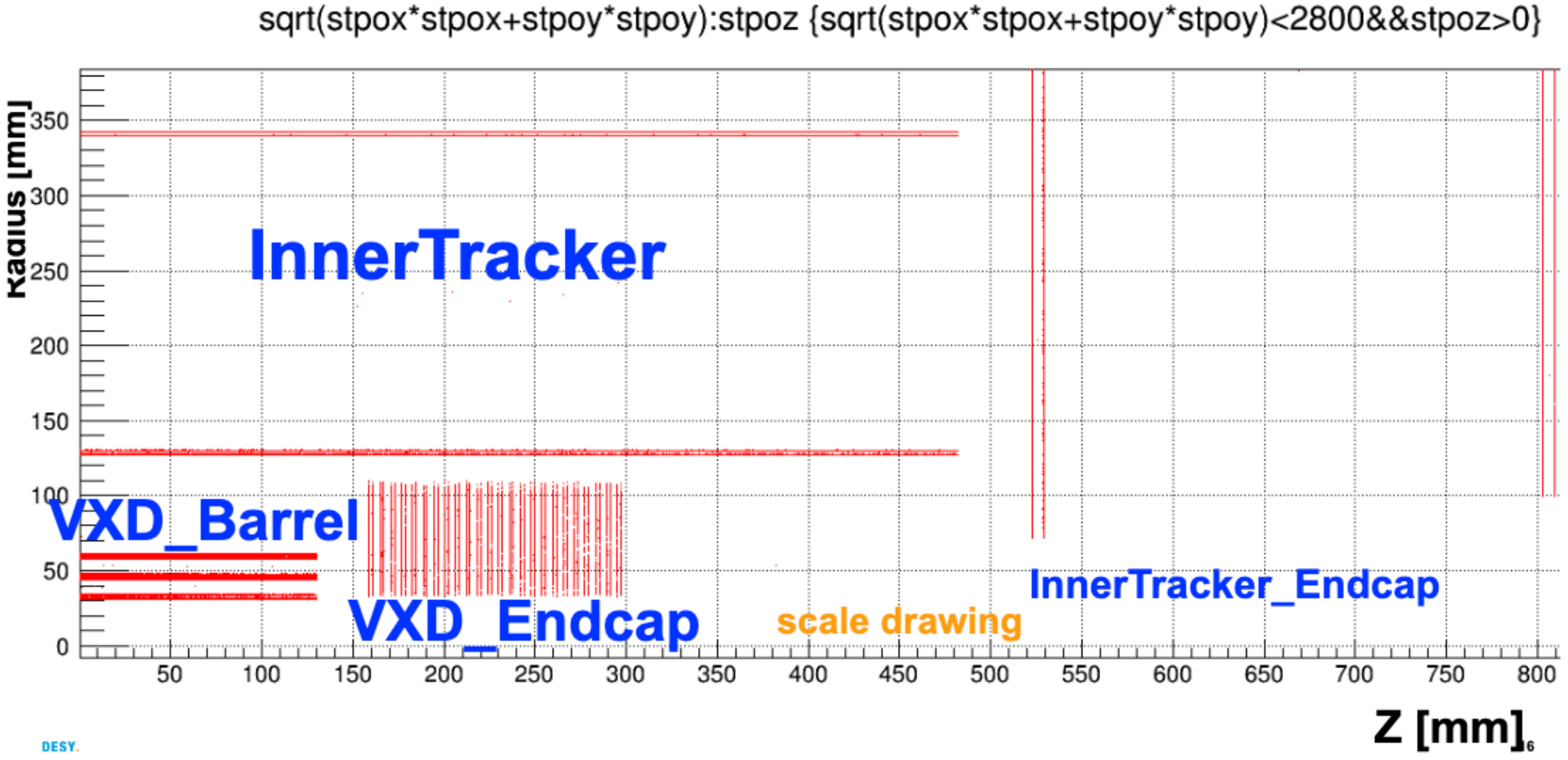
- Example: HNLs
- THUNDERDOME: Totally Hyper-UNrealistic DEtectoR in a huge DOME (maximum distance from IP=100m for comparison)

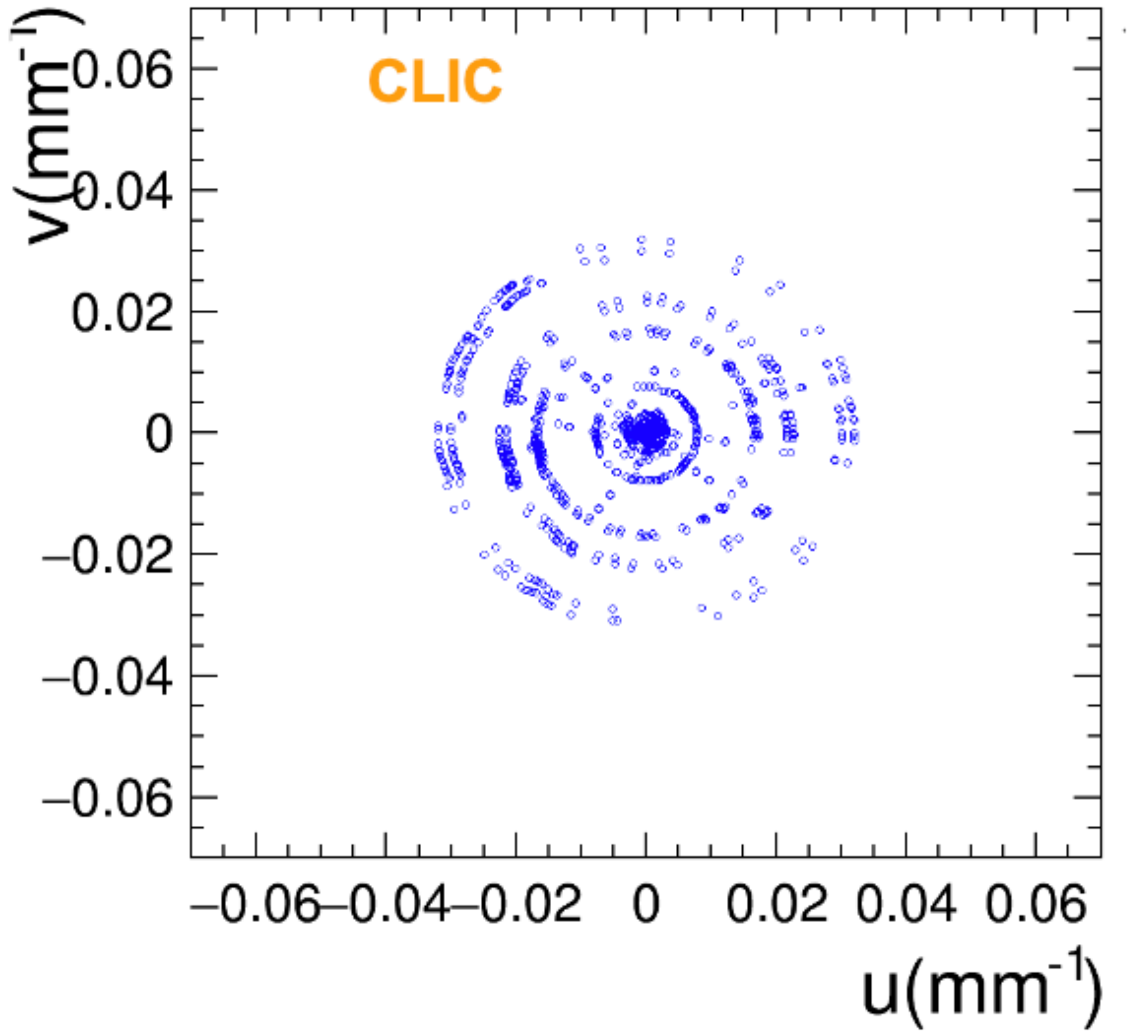
Different inner tracker layouts: ILD and CLICdp

In real and conformal space









DESY.

15

Unconventional tracking

Studies at ILD

- Missing hits in TPC
- Particles travelling alongside the boundaries generate no hits
- Long distance between first hit and true vertex leads to wrong track parameters!

Virtual volumes in the TPC

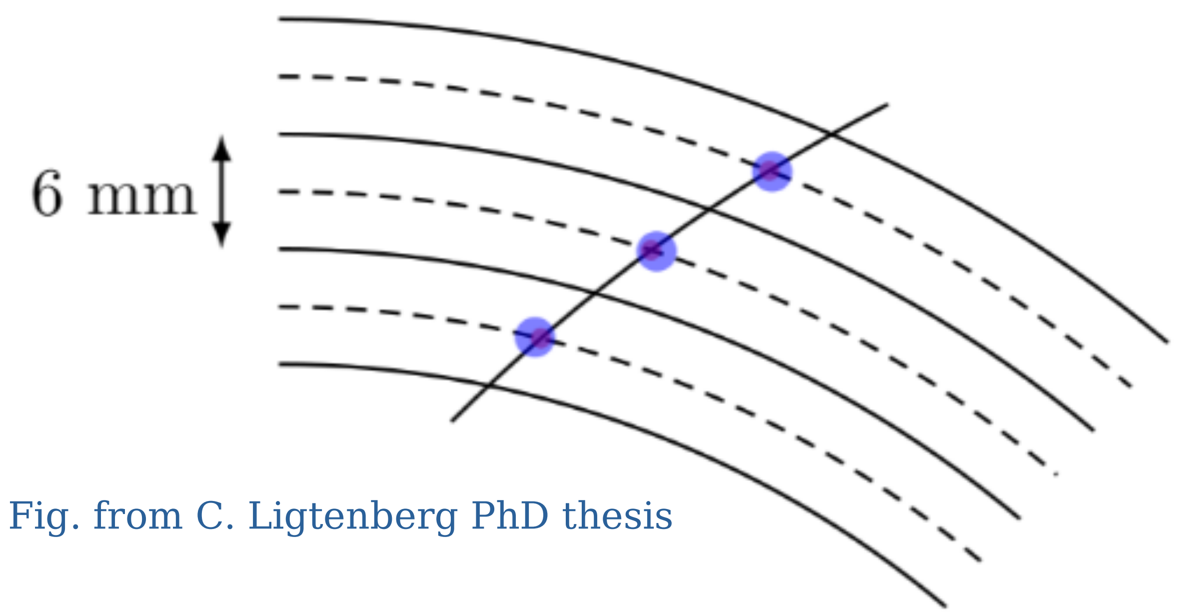
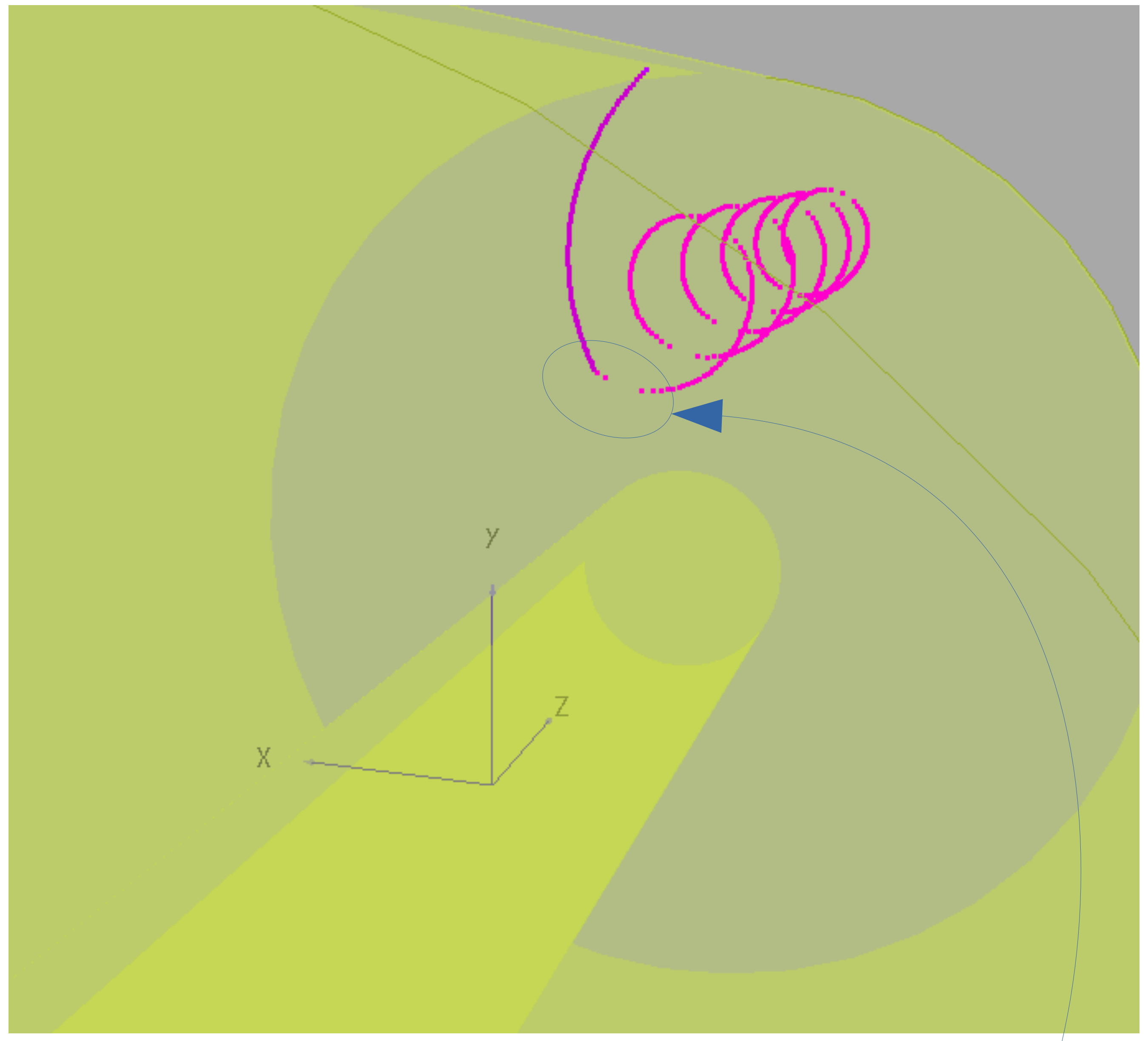


Fig. from C. Ligtenberg PhD thesis

TPC SimTrackerHits

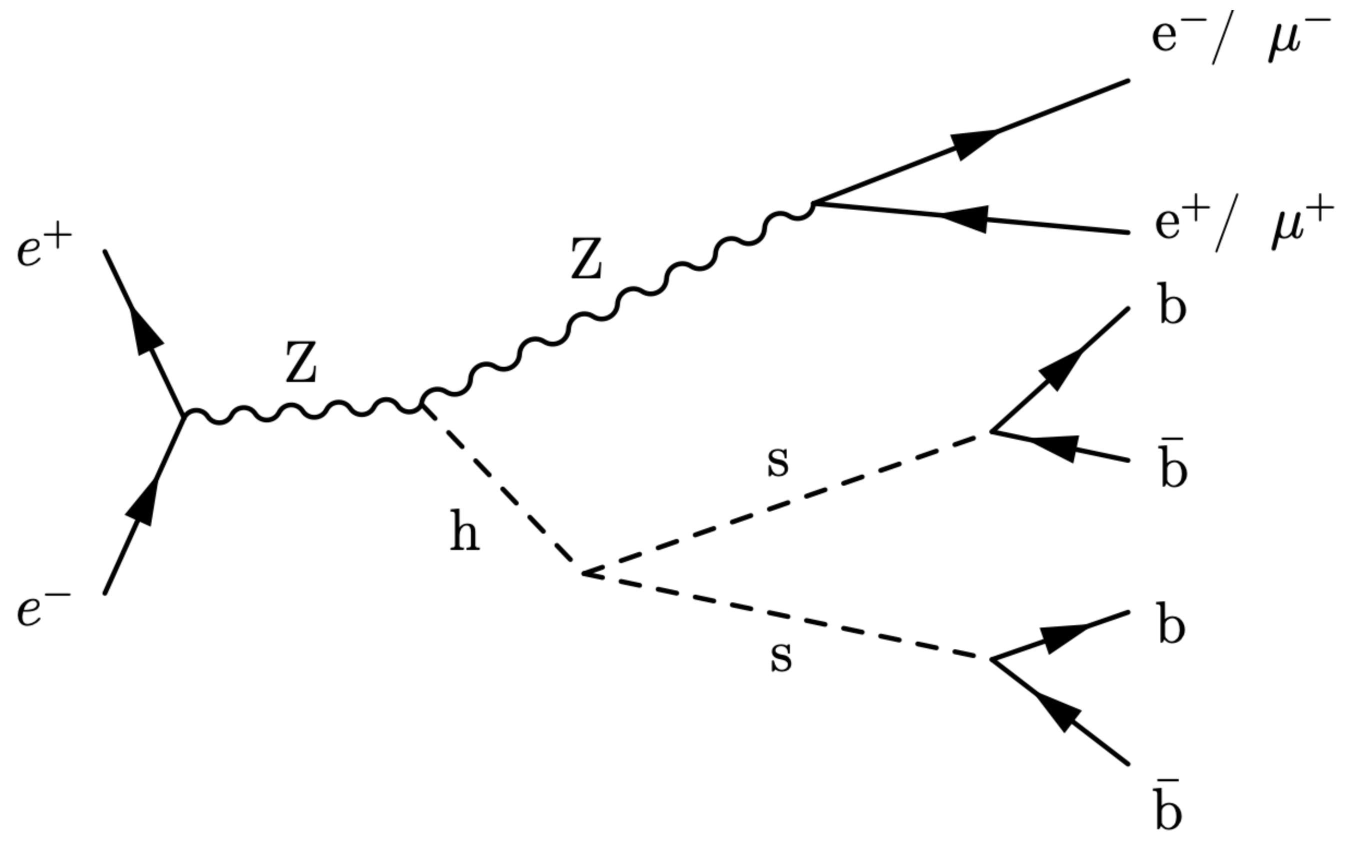


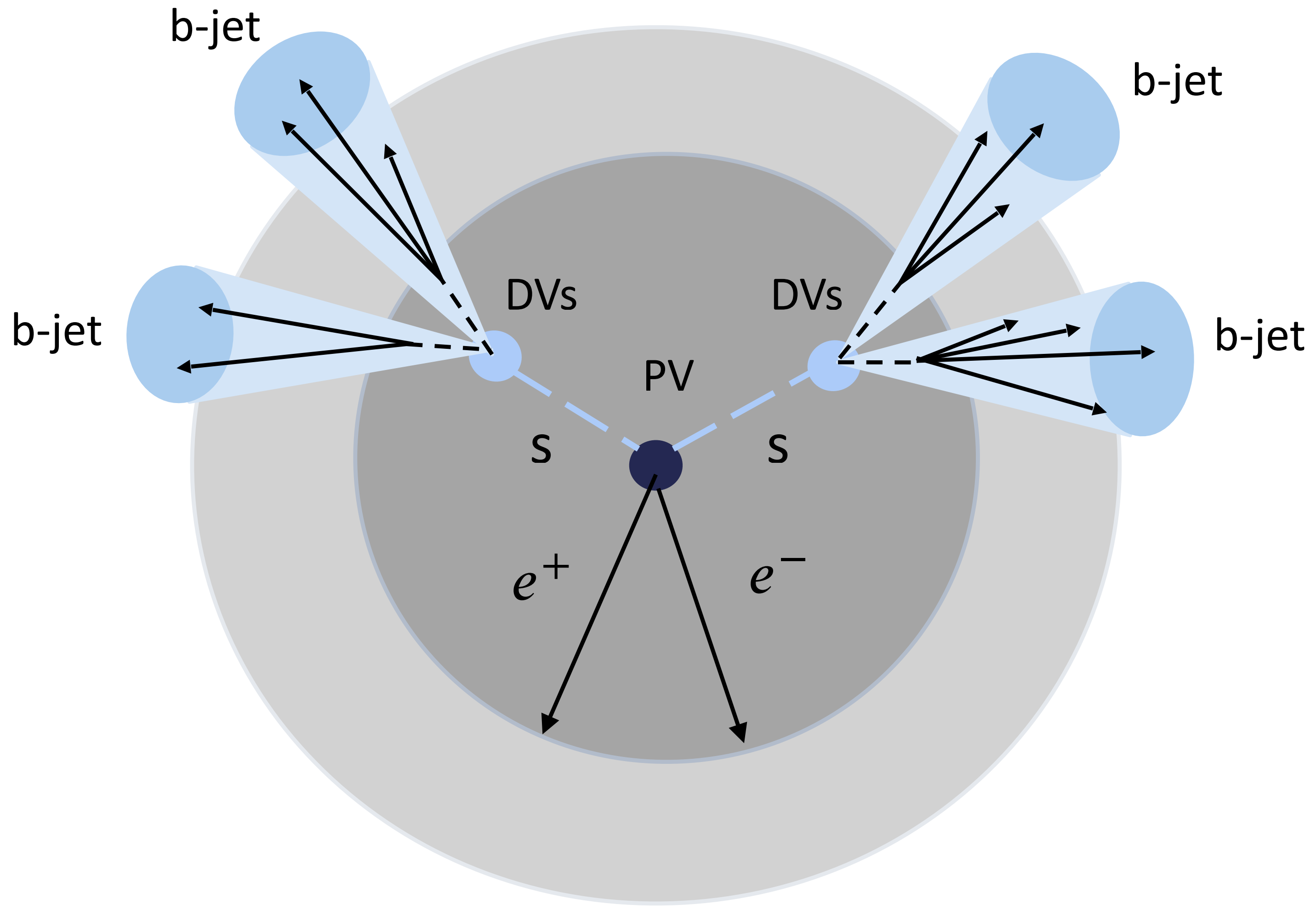
From Jan Klamka

Exotic Higgs decays to LLPs at FCC-ee

- The Higgs boson can have sizeable couplings to new particles → exotic Higgs decays
- Our considered model: SM + scalar (arXiv:1312.4992, arXiv:1412.0018)
- The SM Higgs boson (h) and the scalar (s) mix, governed by the mixing angle sin θ
  - For sufficiently small mixing, the scalar can be long-lived, cτ ~ meters if θ < 1e-6
- Higgs produced at ZH-stage of FCC-ee with $\sqrt{s} = 240\ GeV$
- For plots in these slides $L = 5\ ab^{-1}$ (total integrated luminosity considering the old baseline of 2 IPs)
- Signal process: $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$, probed in events with 2 displaced vertices (DVs) and Z-boson reconstructed from the lepton pair
- Simulations produced using MadGraph v3.4.1 + Pythia8 + DELPHES (fast simulation)

- Considered model parameters:
  - m_s = 20 GeV and m_s = 60 GeV
  - sin θ = 1e-5, 1e-6, 1e-7, corresponding to mean proper lifetimes cτ of O(1 mm – 10 m)



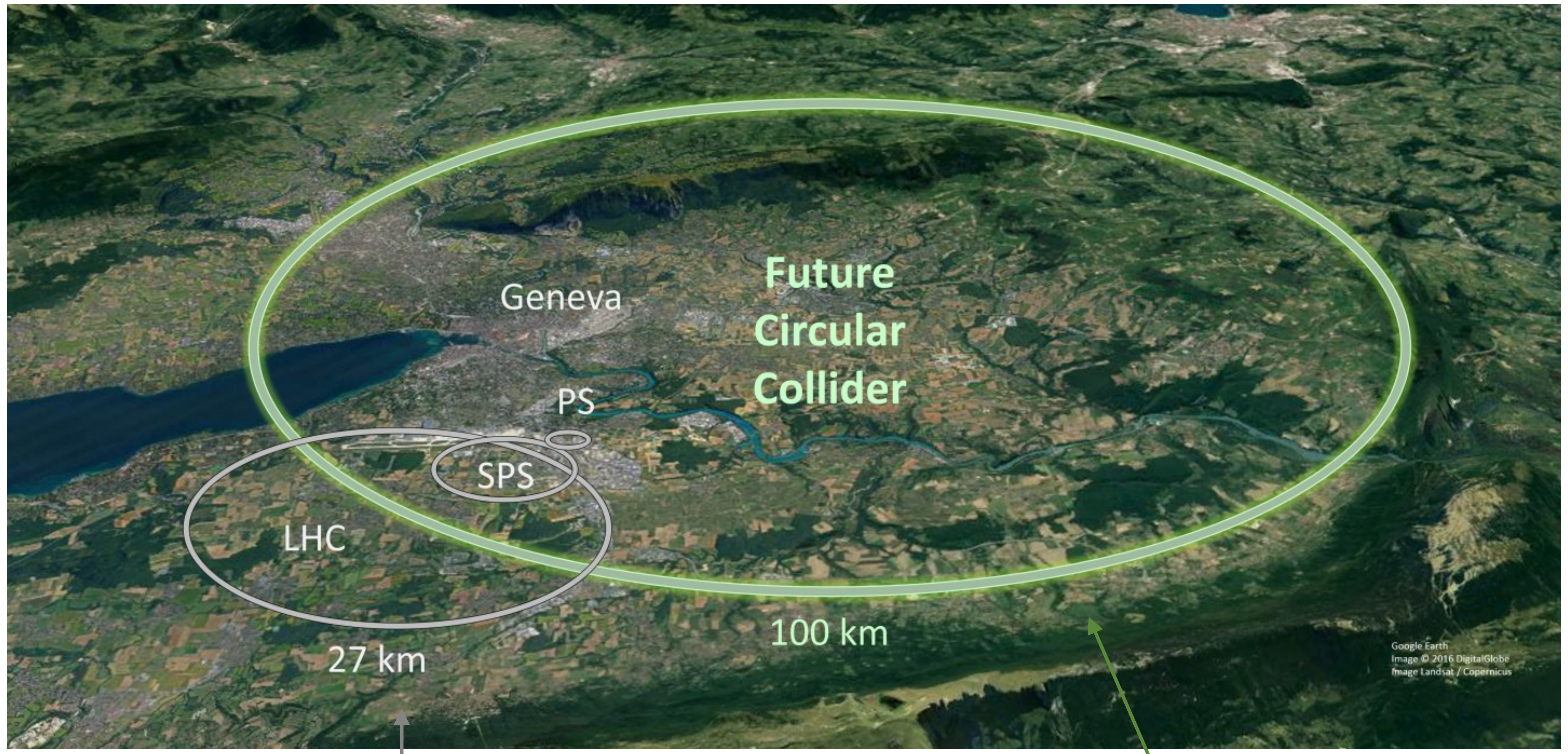


2

From Magdalena Vande Voorde, Giulia Ripellino

The Future Circular Collider (FCC)

- A proposed future accelerator at CERN
- Operate in two stages with physics complementarity:
  - Precision with **FCC-ee**: e^+e^- collisions at four energy stages, i.e an EW, Higgs and top factory at high luminosities
  - Discovery with **FCC-hh**: an energy frontier with hadron collisions at ≥ 100 TeV
- FCC-ee also offers good opportunities for LLP searches!
  - Clean experimental signatures
  - No trigger limitations
  - High luminosity



LHC/LEP:
27 km
91-209 GeV (e^+e^- collisions)
14 TeV (pp collisions)

FCC:
90-100 km
91-365 GeV (e^+e^- collisions)
100 TeV (pp collisions)

From Magdalena Vande Voorde, Giulia Ripellino

Exotic Higgs decays to LLPs at FCC-ee

- The Higgs boson can have sizeable couplings to new particles → exotic Higgs decays
- Our considered model: SM + scalar (arXiv:1312.4992, arXiv:1412.0018)
- There are 3 important free parameters determining the phenomenology:
  - The Higgs-scalar coupling κ, determining the branching ratio of the scalar pair production
  - The mass of the scalar m_S, determining the possible final states of the scalar
  - The mixing angle sin θ, from mixing between the Higgs boson and the scalar
    - For sufficiently small mixing, the scalar can be long-lived
    - cτ ~ meters if θ < 1e-6 → **LLP signature**
- Higgs produced at ZH-stage of FCC-ee with $\sqrt{s} = 240\ GeV$
- Signal process: $e^+e^- \to Z\,h$ with $Z \to e^+e^-$ or $\mu^+\mu^-$ and $h \to ss \to b\bar{b}b\bar{b}$

$$\mathcal{L}_{SM} \ni \underbrace{\frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_s S^4}_{\text{scalar potential}} - \underbrace{\frac{1}{2}\kappa S^2|H|^2}_{\text{portal term}} + \underbrace{\mu^2|H|^2 - \lambda|H|^4}_{\text{Higgs potential}}$$

κ: the Higgs-scalar coupling

$$\mathrm{BR}(h \to ss) = \frac{\kappa^2 v_h^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

$$\Gamma\left(s \to X_{\mathrm{SM}}X_{\mathrm{SM}}\right) = \sin^2\theta\,\Gamma\left(h(m_s) \to X_{\mathrm{SM}}X_{\mathrm{SM}}\right)$$

s: the scalar

sin θ: the mixing angle

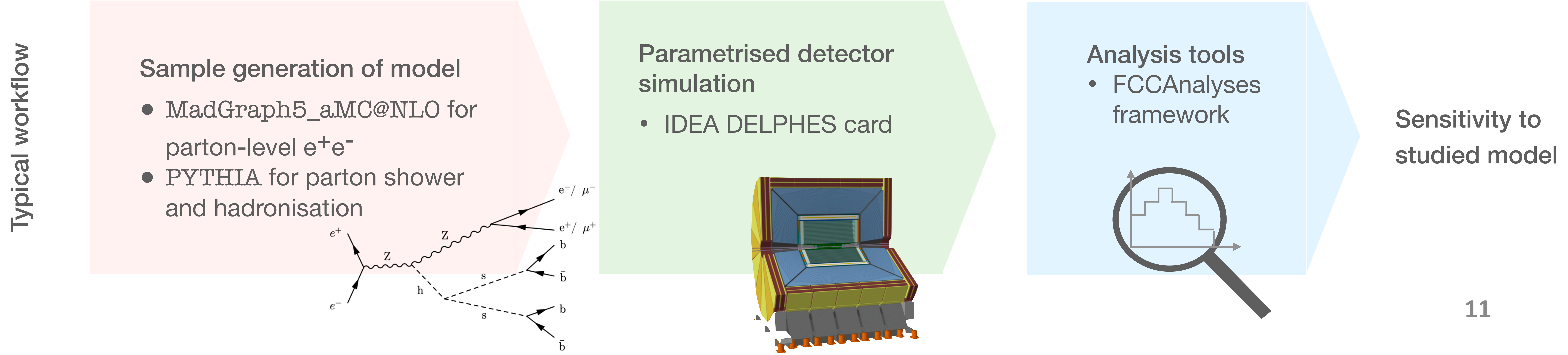
SM particle

10

From Magdalena Vande Voorde, Giulia Ripellino

Simulation of the signal

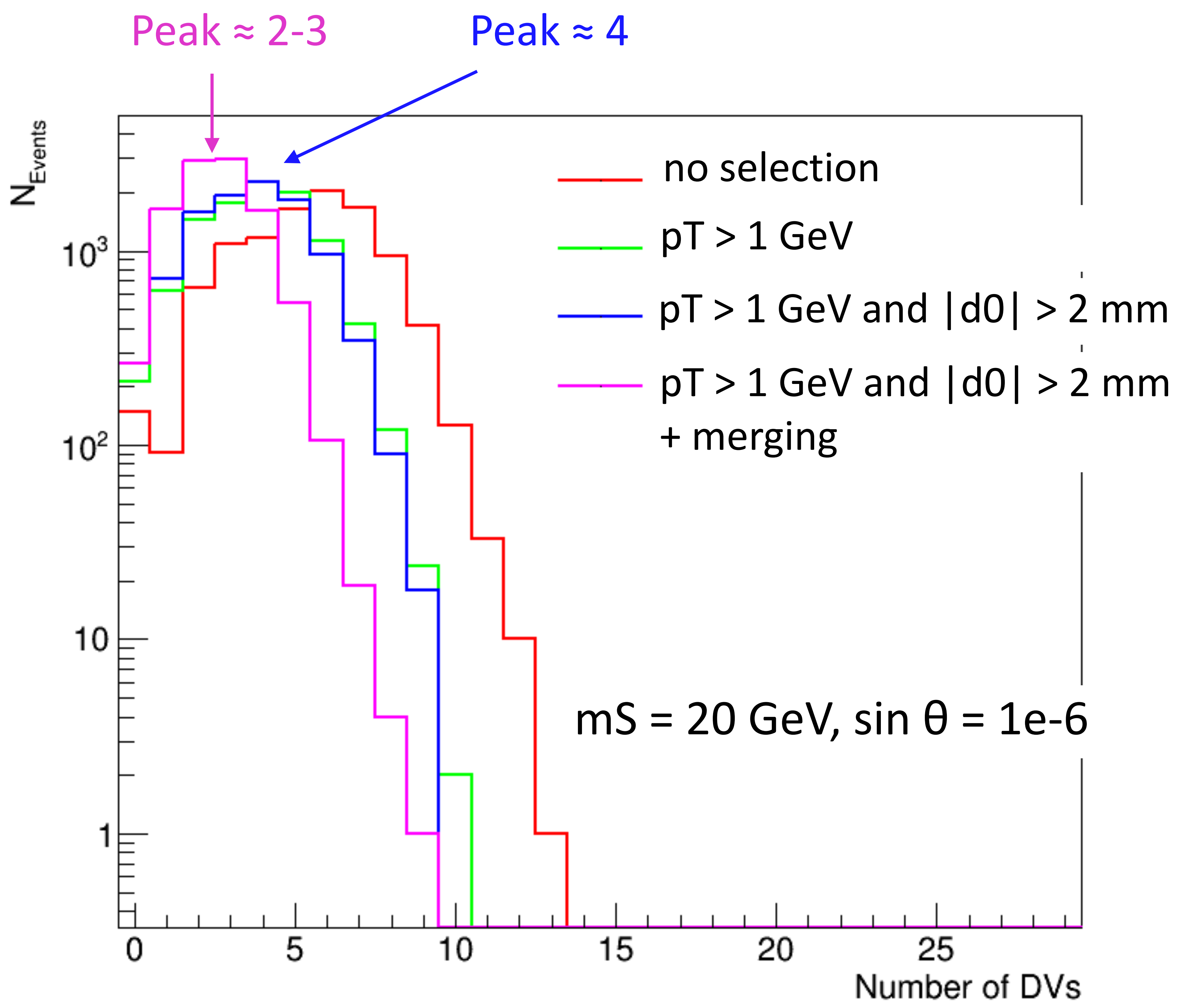
- Generated signal samples: $e^+e^- \rightarrow Z\,h, Z \rightarrow e^+e^-$ or $\mu^+\mu^-, h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
  - Privately produced using MadGraph v3.4.1 + Pythia8 + DELPHES (fast simulation)
  - With the MadGraph5 HAHM (arXiv:1312.4992, arXiv:1412.0018) and the spring2021 IDEA DELPHES card
- Parameters:
  - $\sqrt{s} = 240\ GeV$ and $L = 5\ ab^{-1}$ (total integrated luminosity considering the old baseline of 2 Interaction Points)
  - m_s = 20 GeV and m_s = 60 GeV
  - sin θ = 1e-5, 1e-6, 1e-7, corresponding to mean proper lifetimes cτ of O(1 mm – 10 m)
  - κ = 1e-3

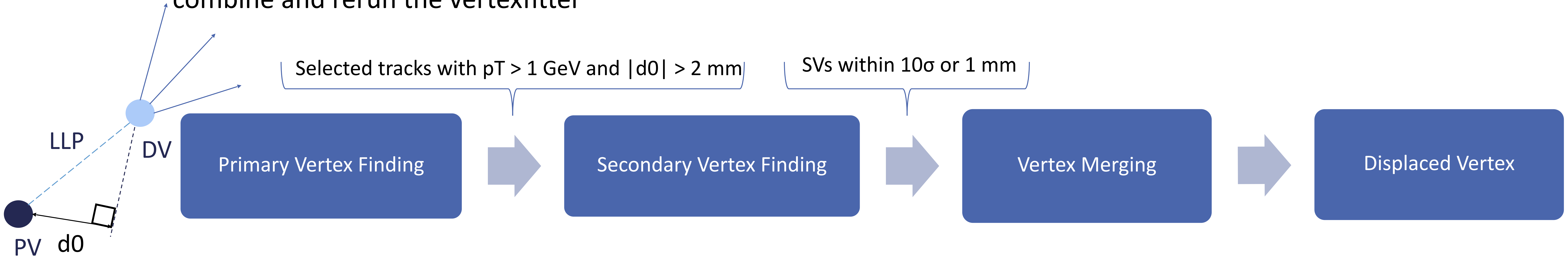


From Magdalena Vande Voorde, Giulia Ripellino

Displaced Vertex reconstruction

- Two options of DV reconstruction implemented and tested, using current tools in the FCCAnalyses framework with extra constraints and functions inspired by ATLAS DV reconstruction (cds)
- SV finder of the LCFI+ algorithm (arXiv:1506.08371), primarily used for flavour-tagging jets (see more in backup)
  - Track selection: pT > 1 GeV and |d0| > 2 mm
  - Inputs for vertex seed: M_{inv} < 40 GeV and $\chi^2 < 9$
  - Vertexing: $\chi^2 < 5$ for adding track to vertex seed
- Added vertex merging in attempt to reconstruct the scalar DVs
  - Compare the vertices positions pair-wise and merge if they are within 10σ (σ = error of vertex position) or 1 mm
  - Merging done by taking the associated tracks of the merged vertices, combine and rerun the vertexfitter

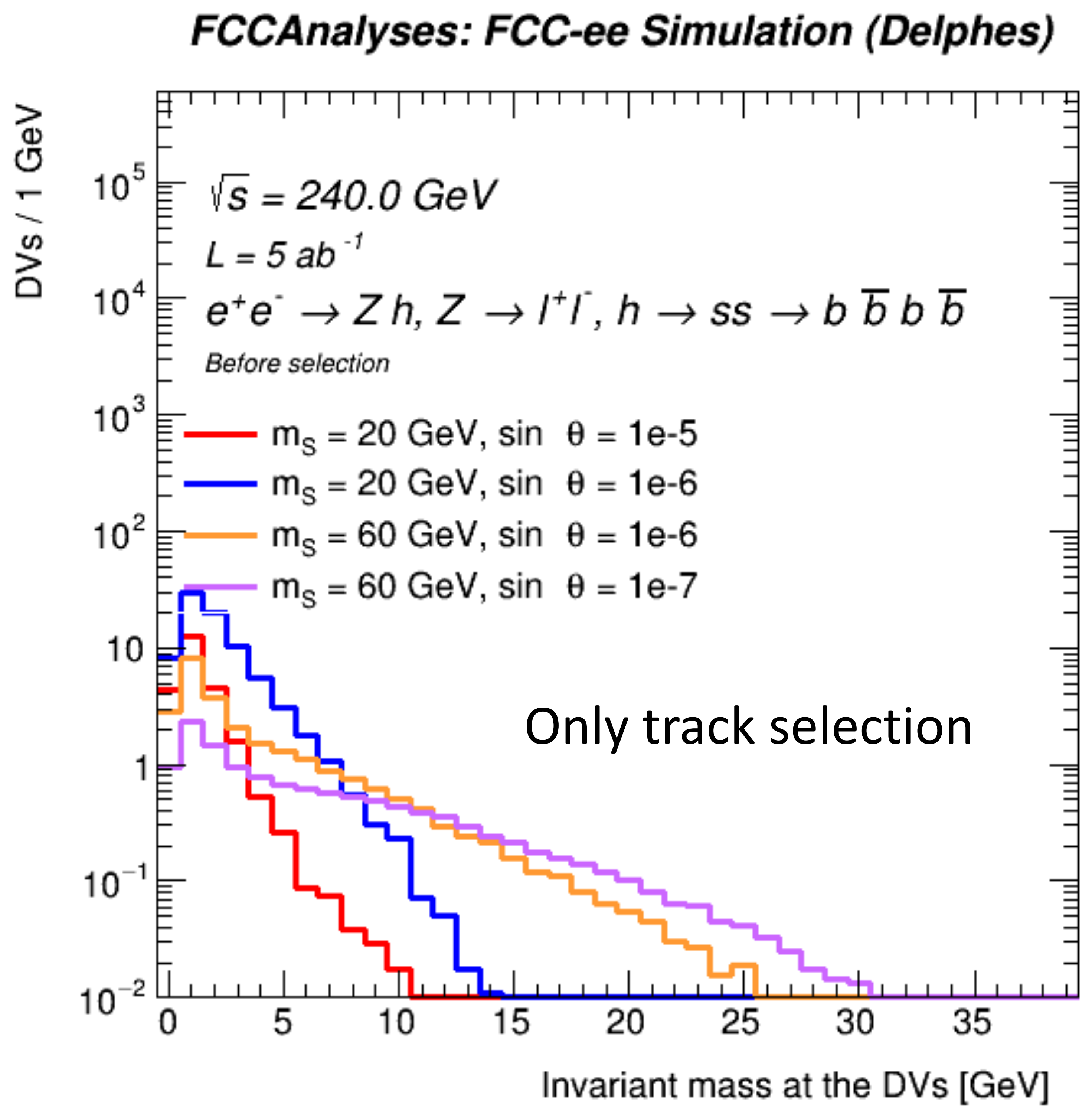


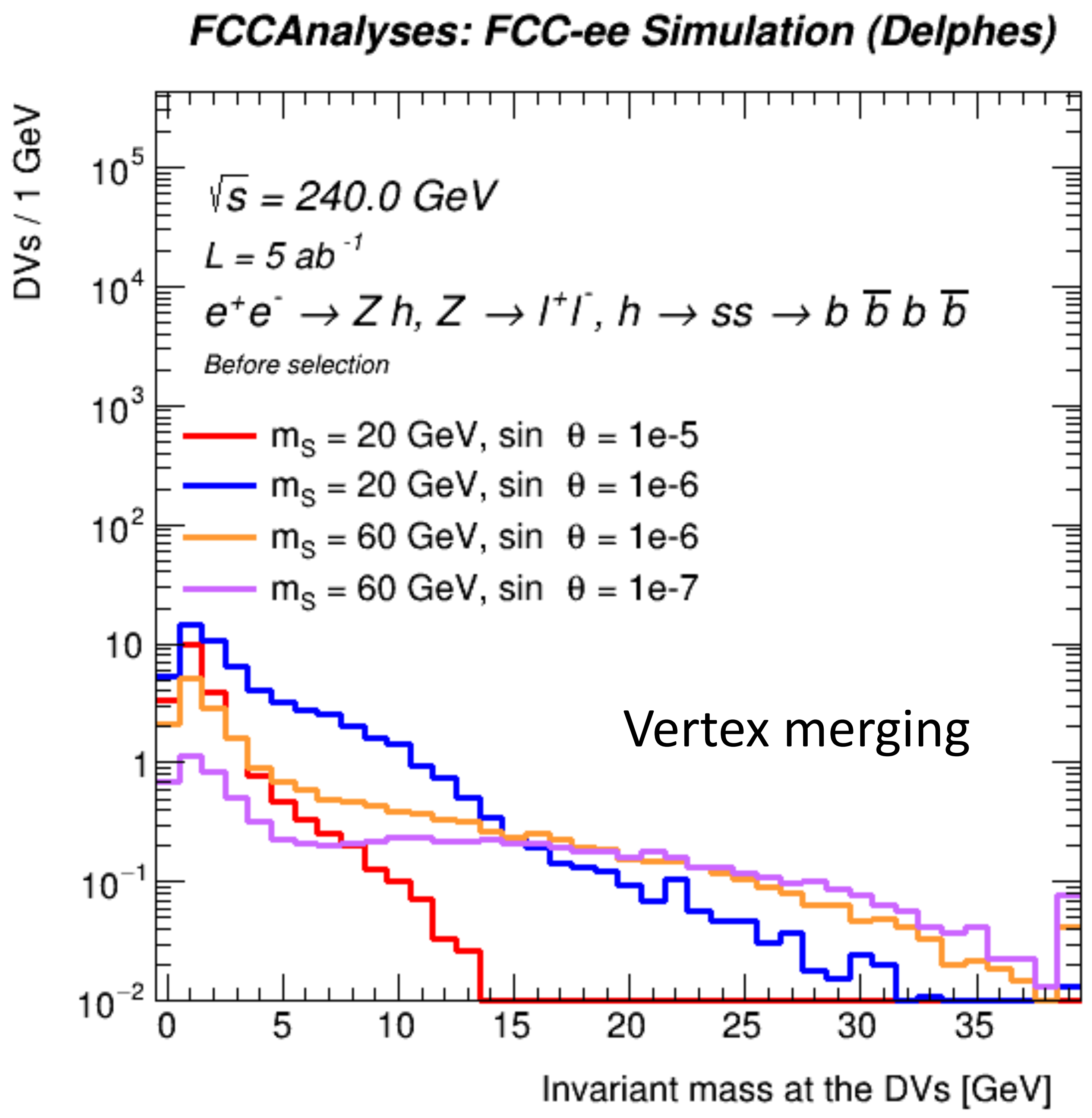


13

From Magdalena Vande Voorde, Giulia Ripellino

Invariant mass at the DVs





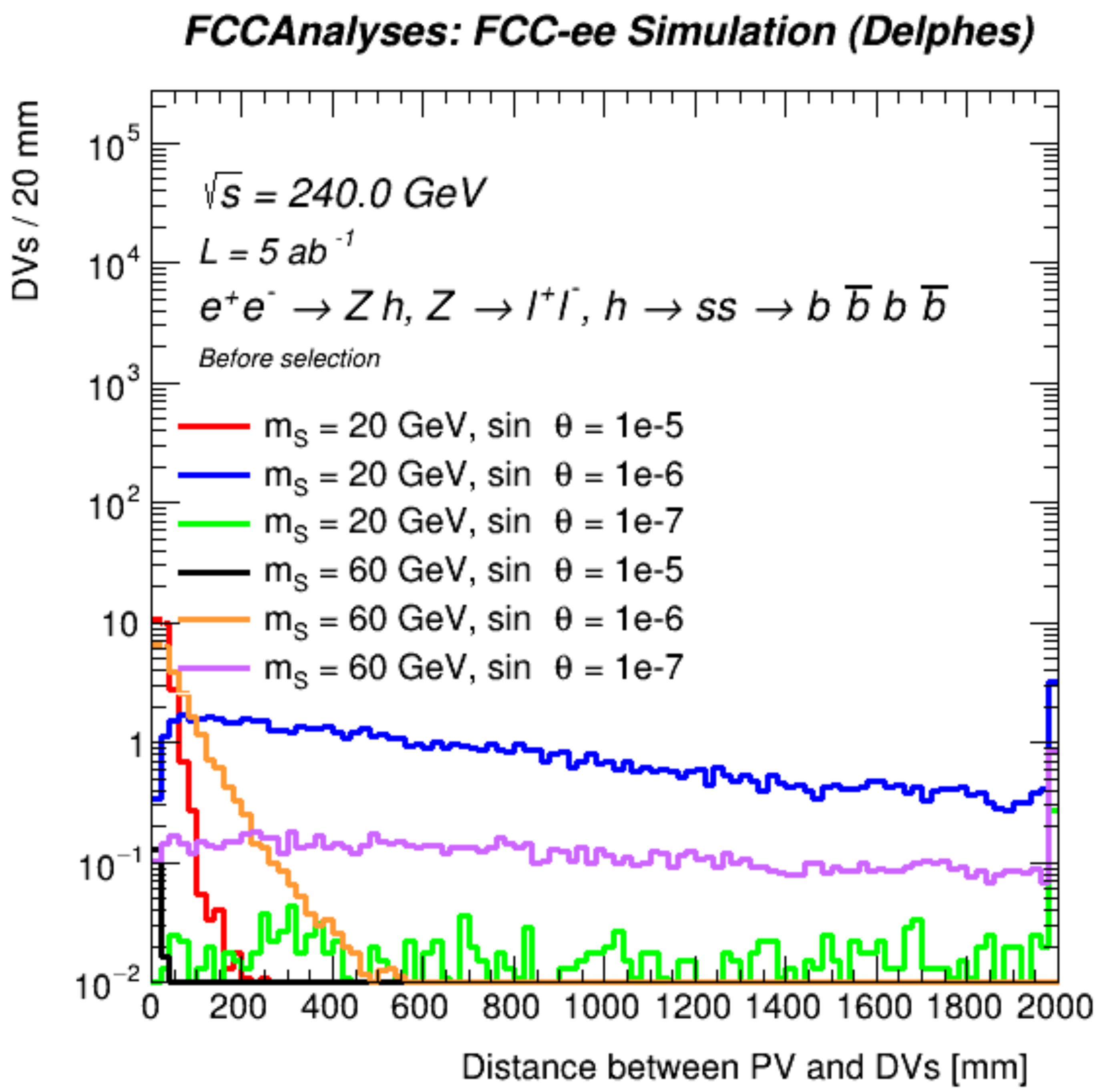
- Usually a good discriminating variable between a DV from an LLP and a fake vertex
- Invariant mass at vertex calculated assuming all tracks to come from pions, this only captures the charged component of the jet fragmentation → expected peak around half of the particle's mass
- More of a structure around higher masses for the merged vertices but no clear peaks
- Tradeoff between goodness-of-fit and invariant mass → no vertex merging at this stage, more truth studies needed! 15

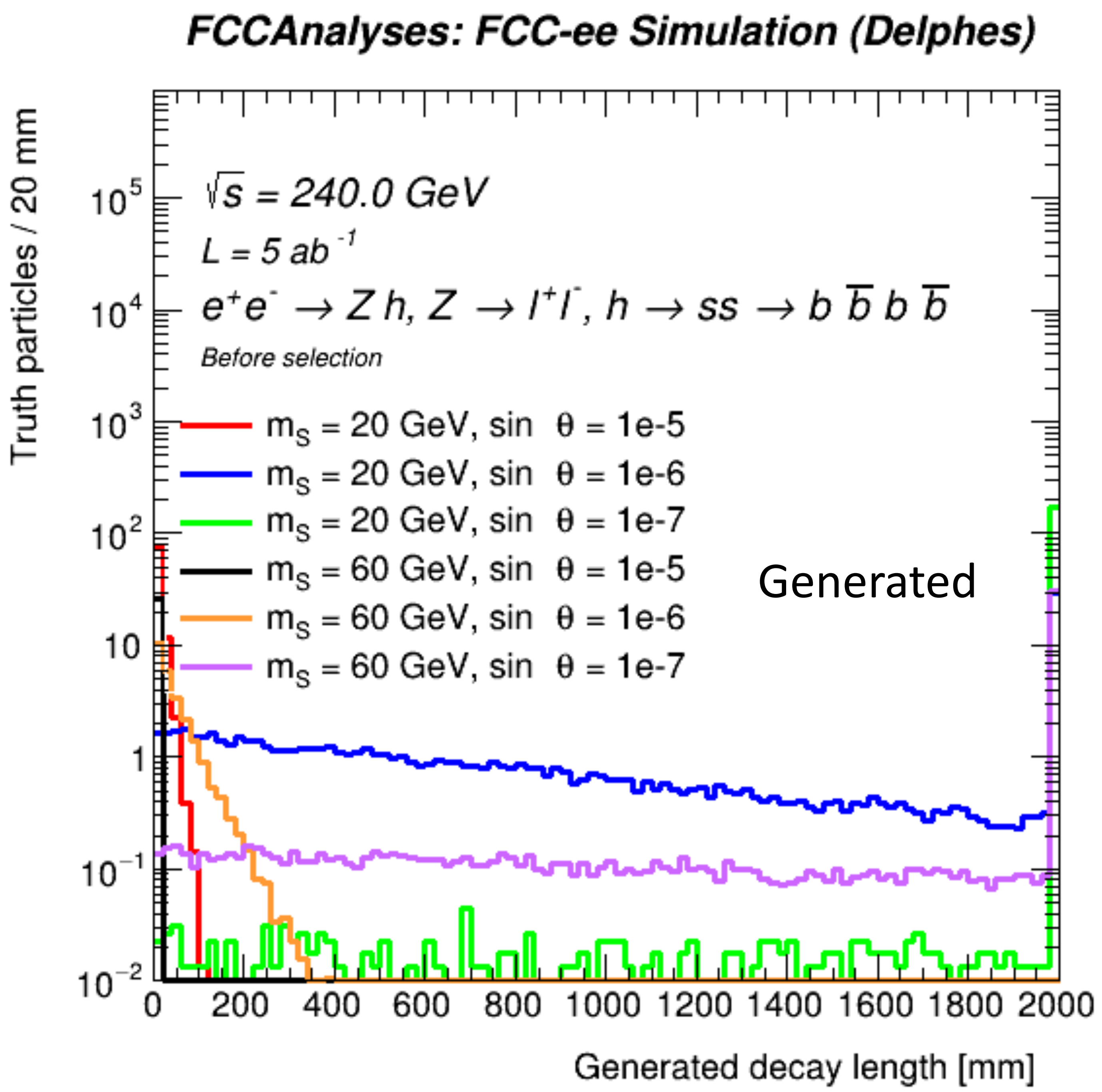
From Magdalena Vande Voorde, Giulia Ripellino

Distance from PV to the DVs

- Usually a good discriminating variable between signal and SM background
- The reconstructed quantity nicely follows the generated quantity
- **m_s = 20 GeV, sin θ = 1e-5**, **m_s = 20 GeV, sin θ = 1e-6**, m_s = 60 GeV, sin θ = 1e-7 and m_s = 60 GeV, sin θ = 1e-6 good for the analysis!
- **m_s = 60 GeV, sin θ = 1e-5** is too short lived to be properly reconstructed with the DV algorithm
- **m_s = 20 GeV, sin θ = 1e-7** might be too long-lived to have enough DVs within DCH (the tracker volume)

Reconstructed DVs with custom track selection





16

From Magdalena Vande Voorde, Giulia Ripellino

Vertex reconstruction, further reading

- More details in thesis: DiVA
- LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies: arXiv:1506.08371
- FCCAnalyses framework vertex reconstruction: GitHub

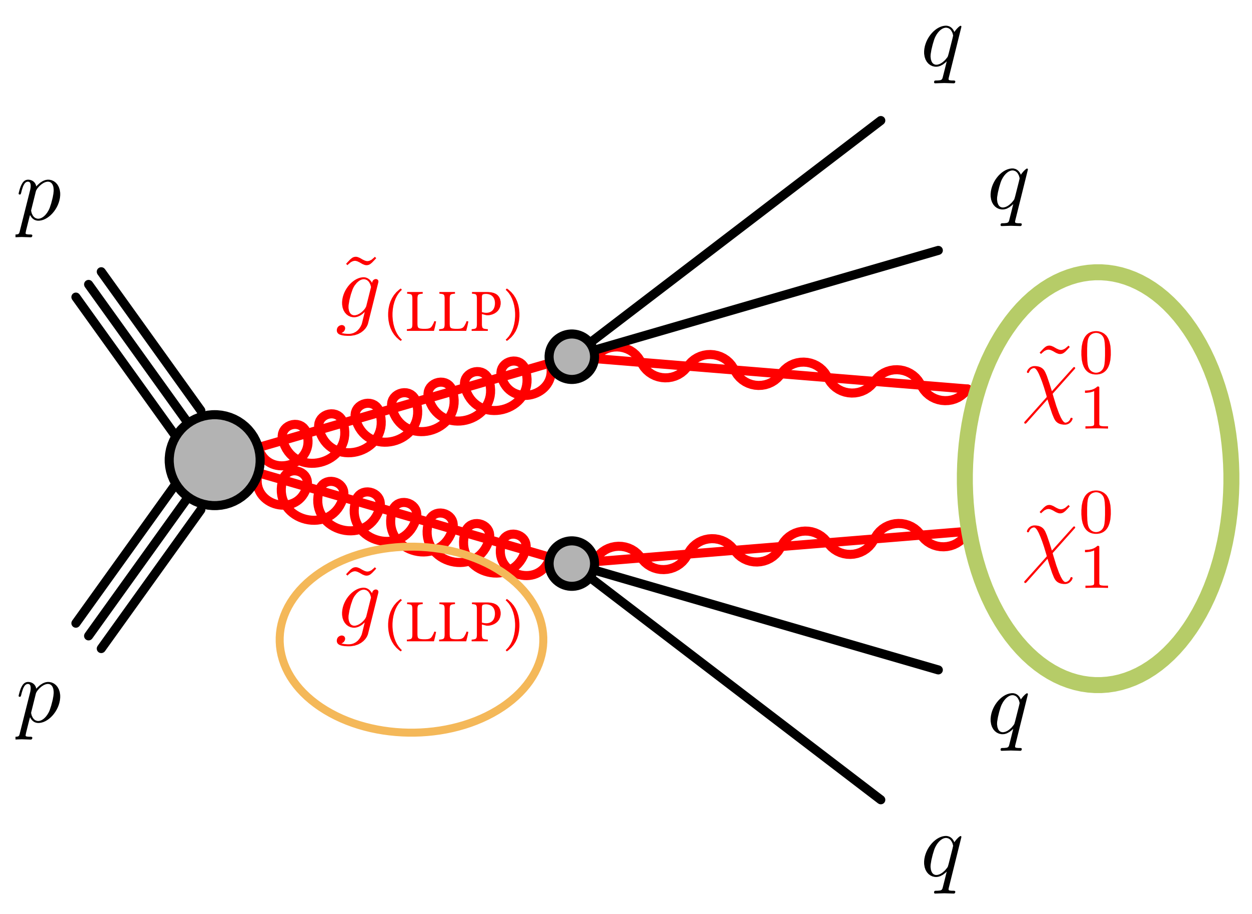
17

From Magdalena Vande Voorde, Giulia Ripellino

Charged LLPs Large dE/dx

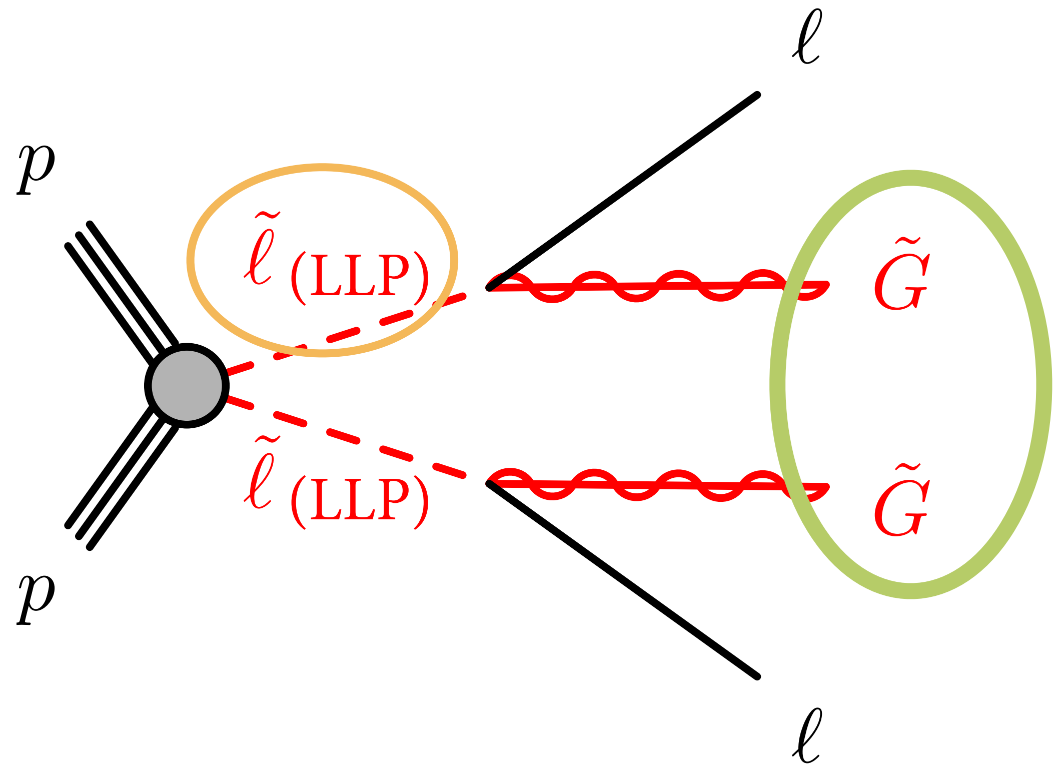
SUSY-2018-42 2205.06013

- Pair production of several different long-lived sparticles of charge $|q|$ = 1
  - isolated tracks with high transverse momenta (pT) and anomalously large specific ionisation losses (dE/dx)
  - particles are expected to move significantly slower than the speed of light
  - Use MET triggers
  - Fully data-driven background estimation!



High pT track with large dE/dx

LSP = MET



Charged LLPs Large dE/dx

SUSY-2018-42 2205.06013

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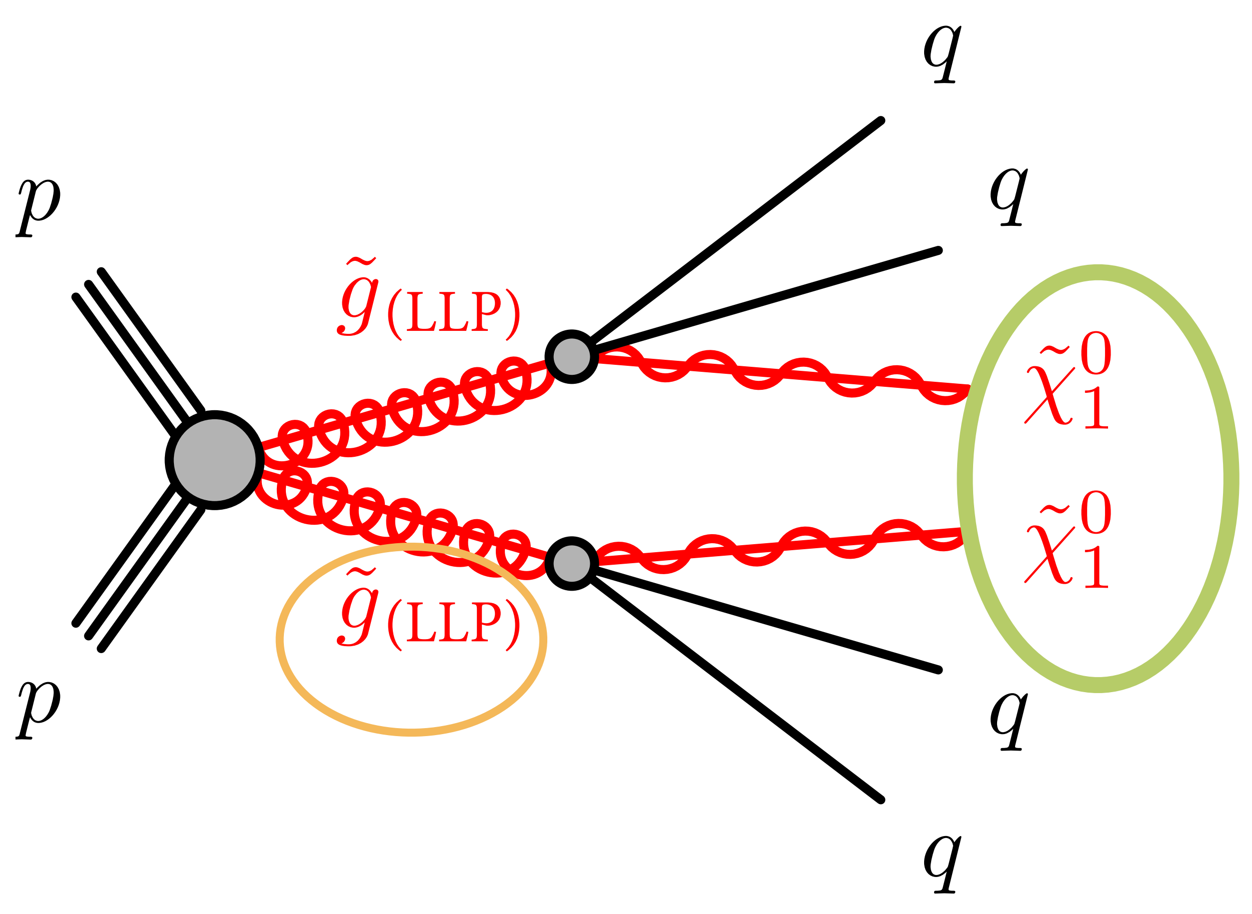
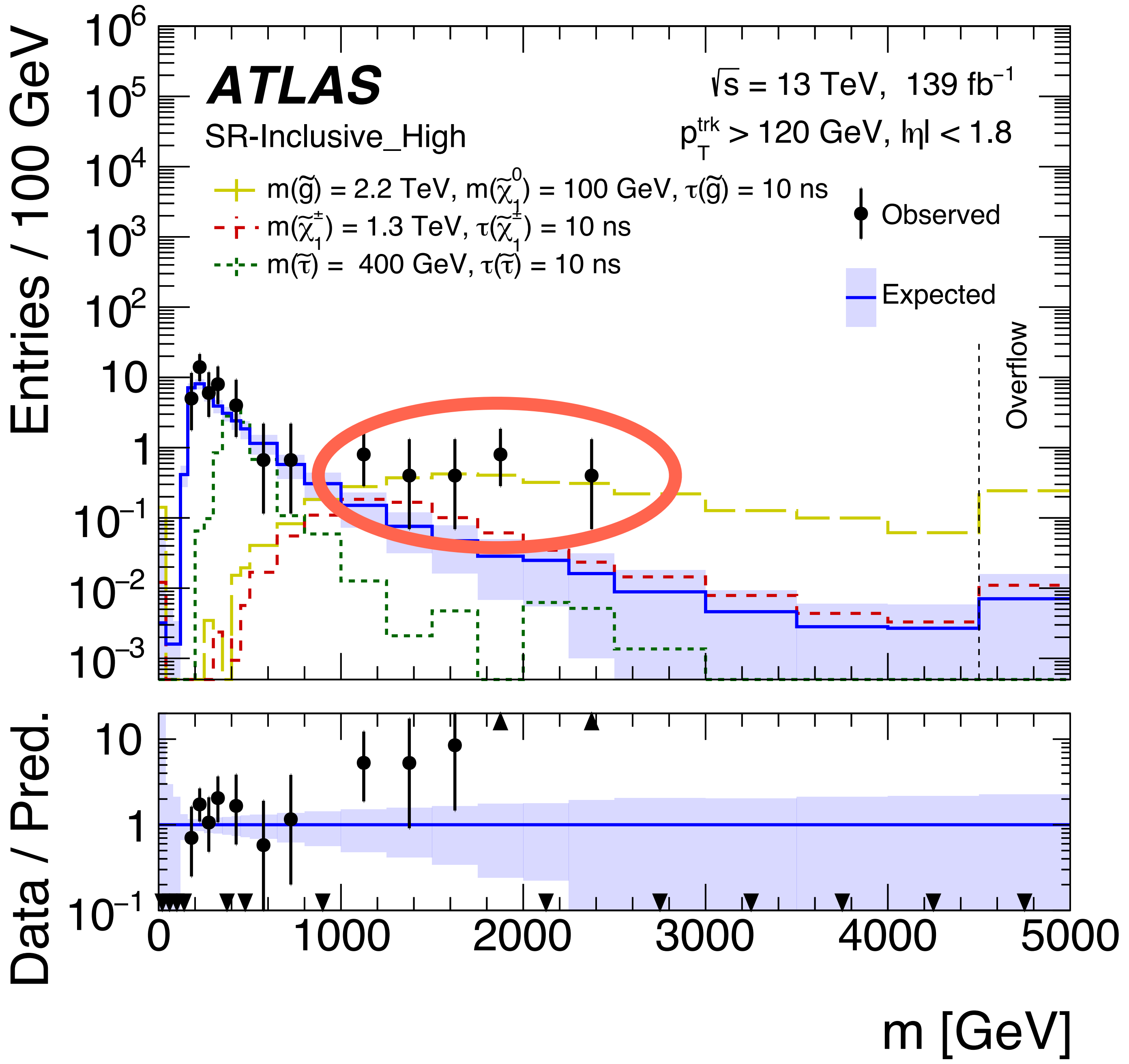


Target mass [GeV]	Mass window [GeV]	Exp.	Obs.	p_0	Z_{local}	$S^{95}_{exp.}$	$S^{95}_{obs.}$
		...egion bin					
		SR-Inclusive_High					
		...ifetime					
200	[120, 225]	5.6 ± 0.7	7	2.65×10^{-1}	0.6	$6.3^{+2.5}_{-1.7}$	7.8
300	[200, 350]	9.2 ± 0.8	14	7.11×10^{-2}	1.5	$7.6^{+3.0}_{-2.1}$	12.5
400	[300, 500]	5.8 ± 0.4	6	4.39×10^{-1}	0.1	$6.1^{+2.5}_{-1.8}$	6.5
450	[350, 600]	5.1 ± 0.4	3	5.00×10^{-1}	0.0	$6.0^{+2.2}_{-1.6}$	4.6
500	[400, 700]	4.3 ± 0.4	4	5.00×10^{-1}	0.0	$5.4^{+2.2}_{-1.3}$	5.2
550	[400, 800]	4.8 ± 0.4	4	5.00×10^{-1}	0.0	$5.8^{+2.5}_{-1.8}$	5.4
600	[450, 900]	3.91 ± 0.31	2	5.00×10^{-1}	0.0	$5.5^{+2.2}_{-1.6}$	4.0
650	[500, 1000]	3.22 ± 0.31	2	5.00×10^{-1}	0.0	$5.2^{+1.9}_{-1.6}$	4.4
700	[550, 1100]	2.64 ± 0.31	2	5.00×10^{-1}	0.0	$4.7^{+1.9}_{-1.0}$	4.3
800	[600, 1200]	2.22 ± 0.24	3	2.86×10^{-1}	0.6	$4.5^{+1.8}_{-1.0}$	5.5
900	[650, 1400]	2.0 ± 0.3	4	9.74×10^{-2}	1.3	$4.3^{+1.6}_{-0.9}$	6.8
1000	[700, 1850]	1.9 ± 0.5	4	9.01×10^{-2}	1.3	$4.1^{+1.9}_{-0.7}$	7.0
1200	[800, 2400]	1.5 ± 0.7	6	9.10×10^{-3}	2.4	$4.0^{+1.6}_{-0.8}$	10.0
1400	[900, 2900]	1.1 ± 0.7	7	2.08×10^{-3}	2.9	$4.0^{+1.4}_{-0.7}$	11.5
1600	[1000, 3450]	0.9 ± 0.5	7	6.03×10^{-4}	3.2	$3.6^{+1.5}_{-0.5}$	11.8
1800	[1100, 4000]	0.8 ± 0.6	7	8.87×10^{-4}	3.1	$3.5^{+1.1}_{-0.2}$	11.9
2000	[1200, 4600]	0.6 ± 0.5	5	4.92×10^{-3}	2.6	$3.1^{+1.1}_{-0.1}$	9.4



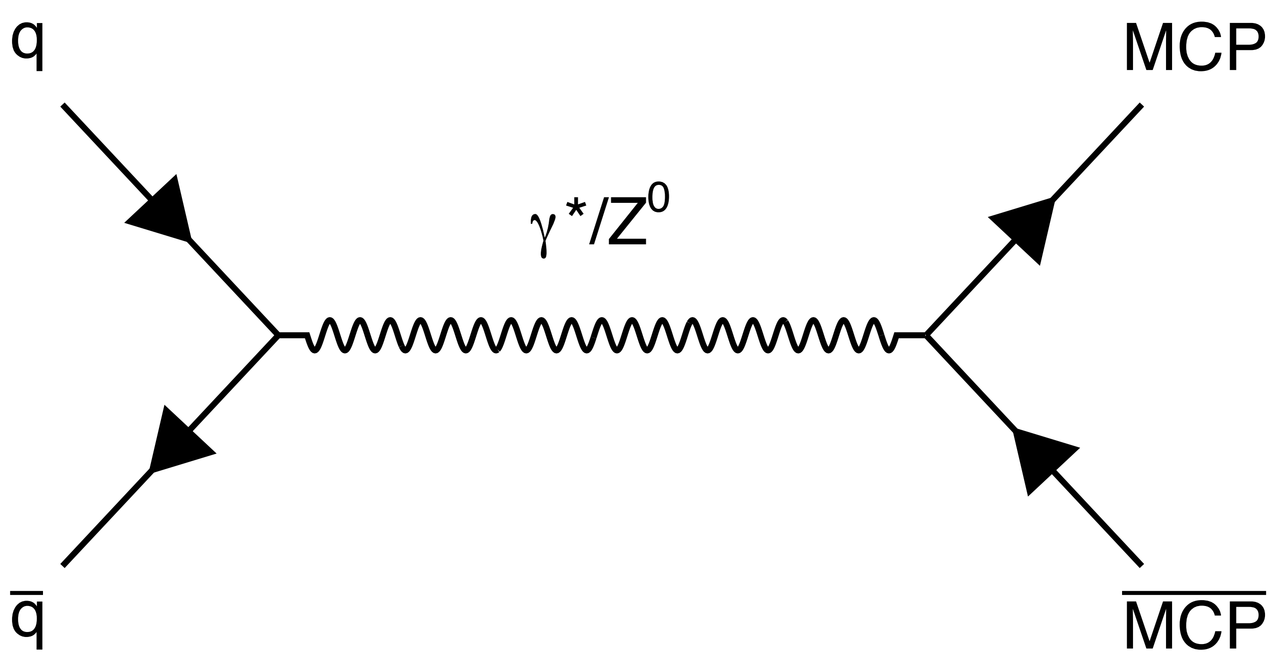
3.6 σ excess!!

Is this New Physics???
Maybe, though… from the TOF of these events indicate that none of the candidate tracks are from charged particles moving significantly slower than the speed of light ☹

CMS doing a similar analysis
Analysis will be repeated in Run 3!

Multicharged particles

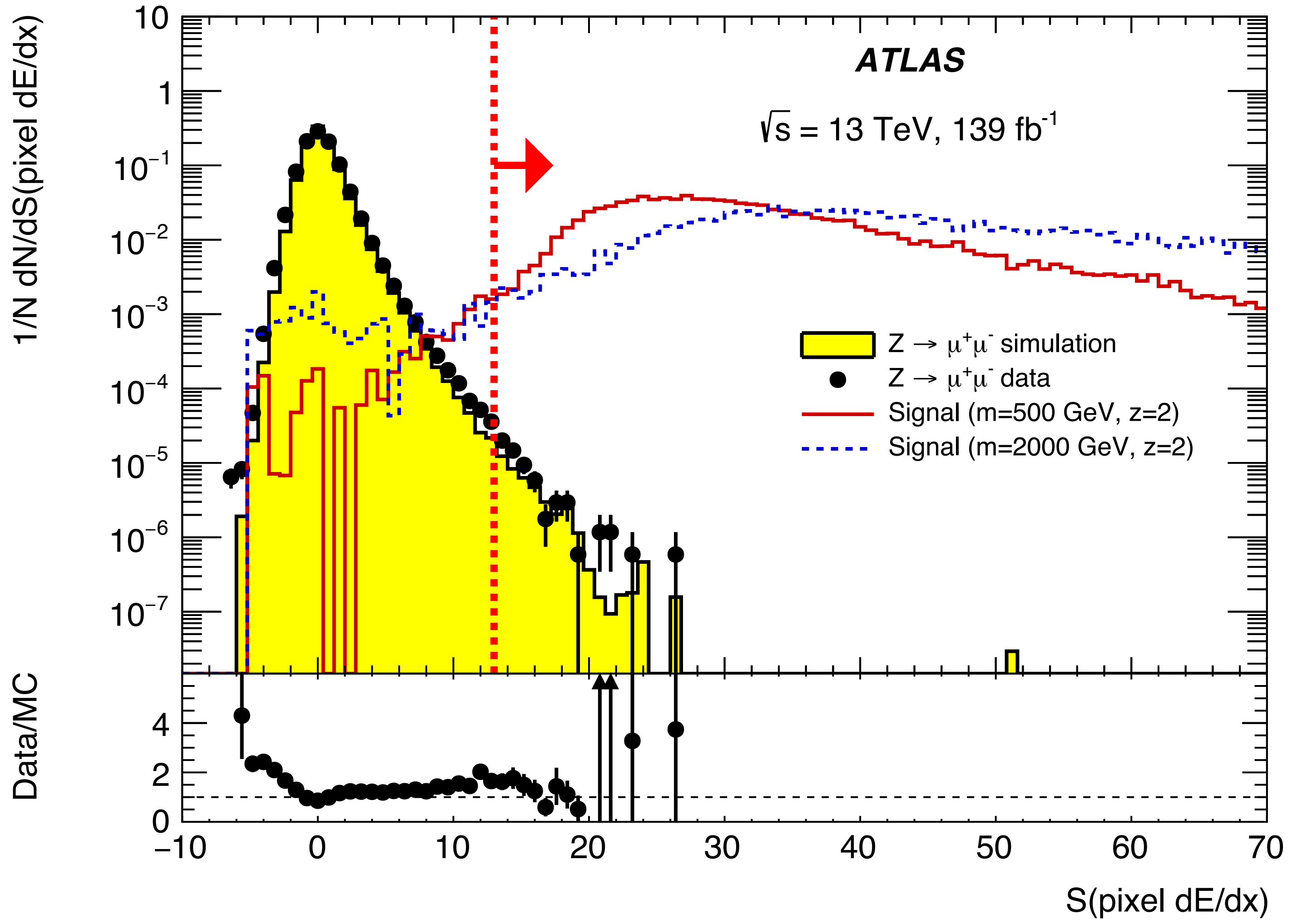
EXOT-2018-54



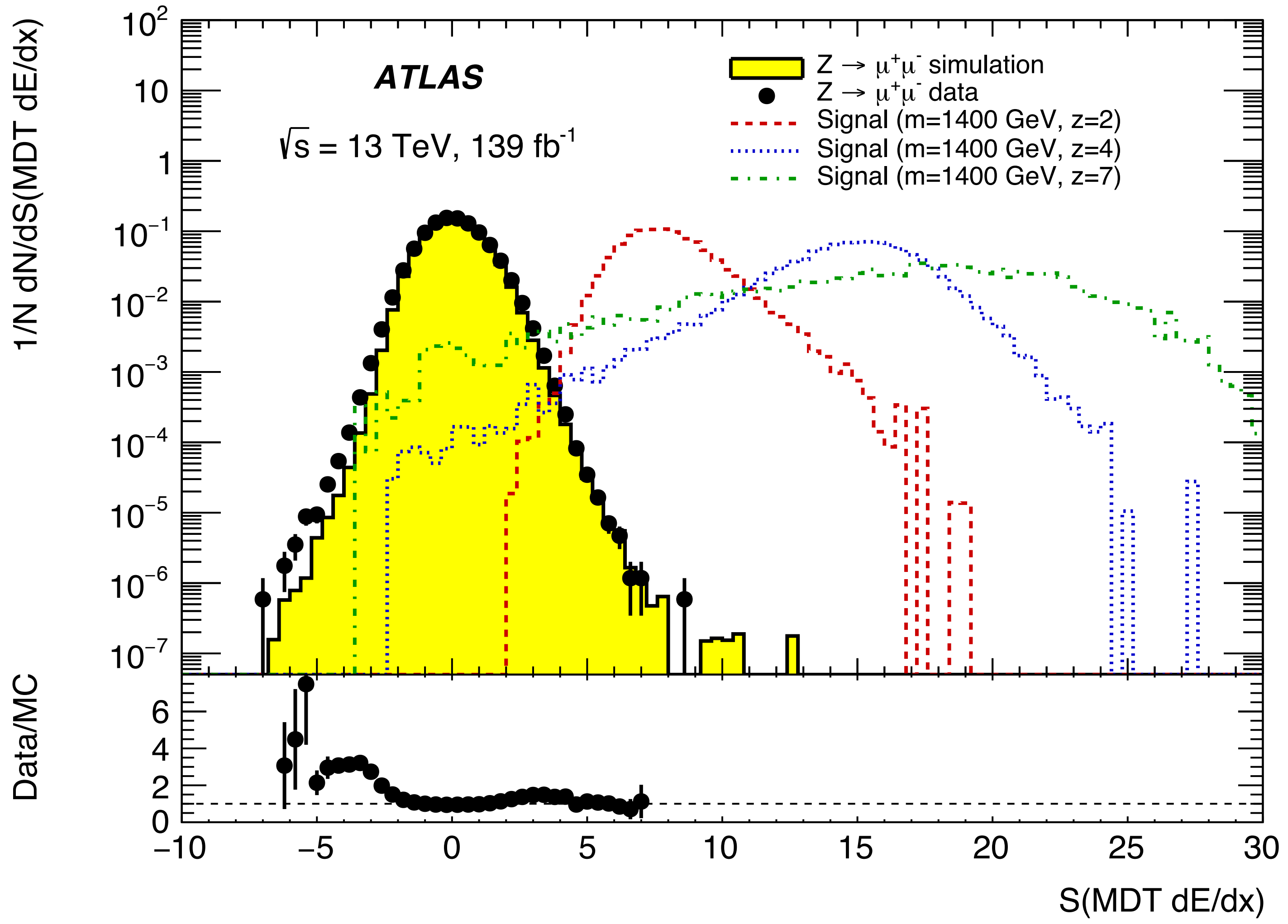
- Search for heavy long-lived multi-charged particles (MCP) with high ionization (higher electric charges and lower velocities)
  - mass range from 500 to 2000 GeV with electric charges from $|q| = 2e$ to $|q| = 7e$
  - live long enough to traverse the entire ATLAS detector

- Triggers: Muon, MET, late-muon trigger
- Select high-pT muon-like tracks with high dE/dx values in several subdetector systems: pixel ID, TRT, MDT
  - significance: comparing dE/dx with the average value for a highly relativistic muon

z=2

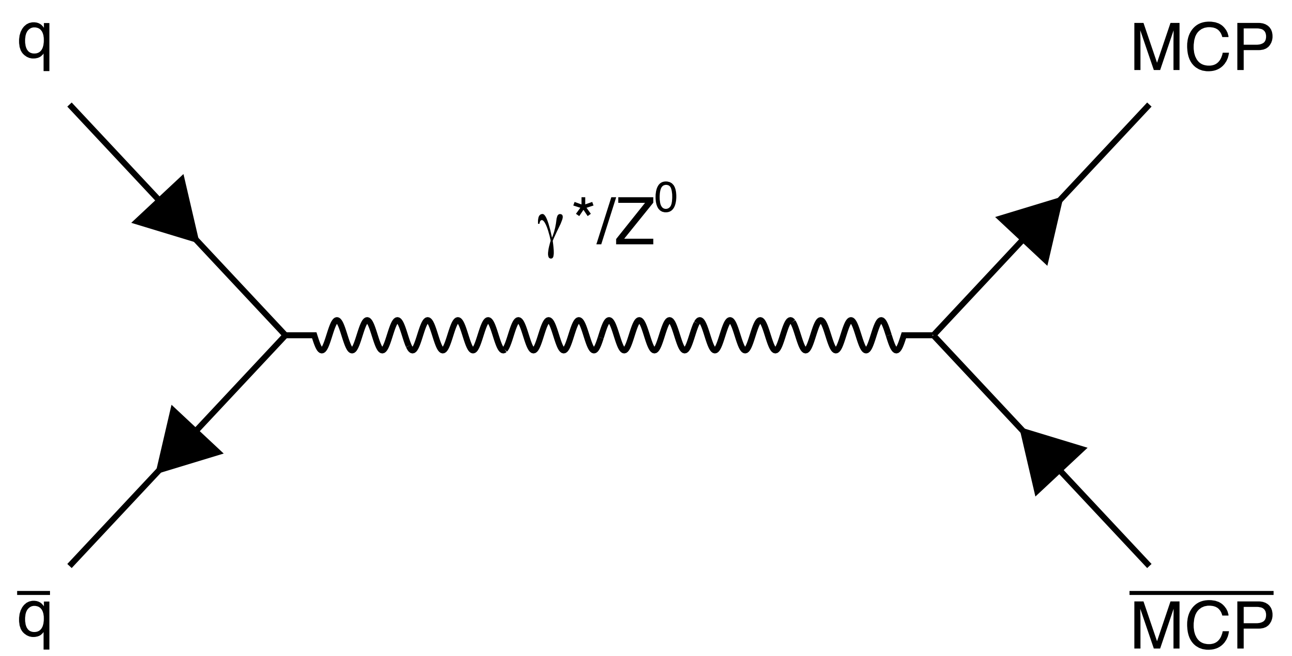


z>2



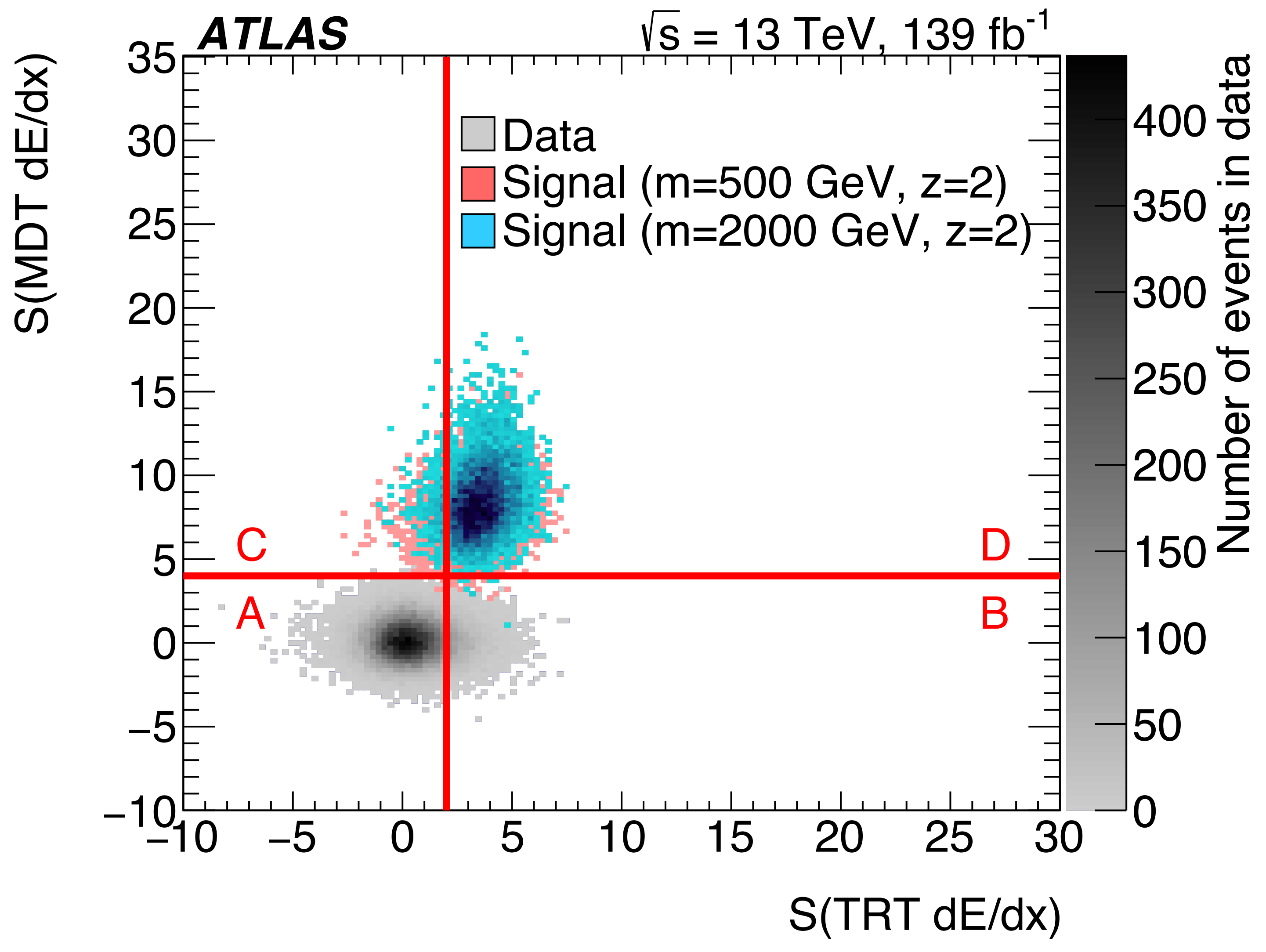
Multicharged particles

[EXOT-2018-54]

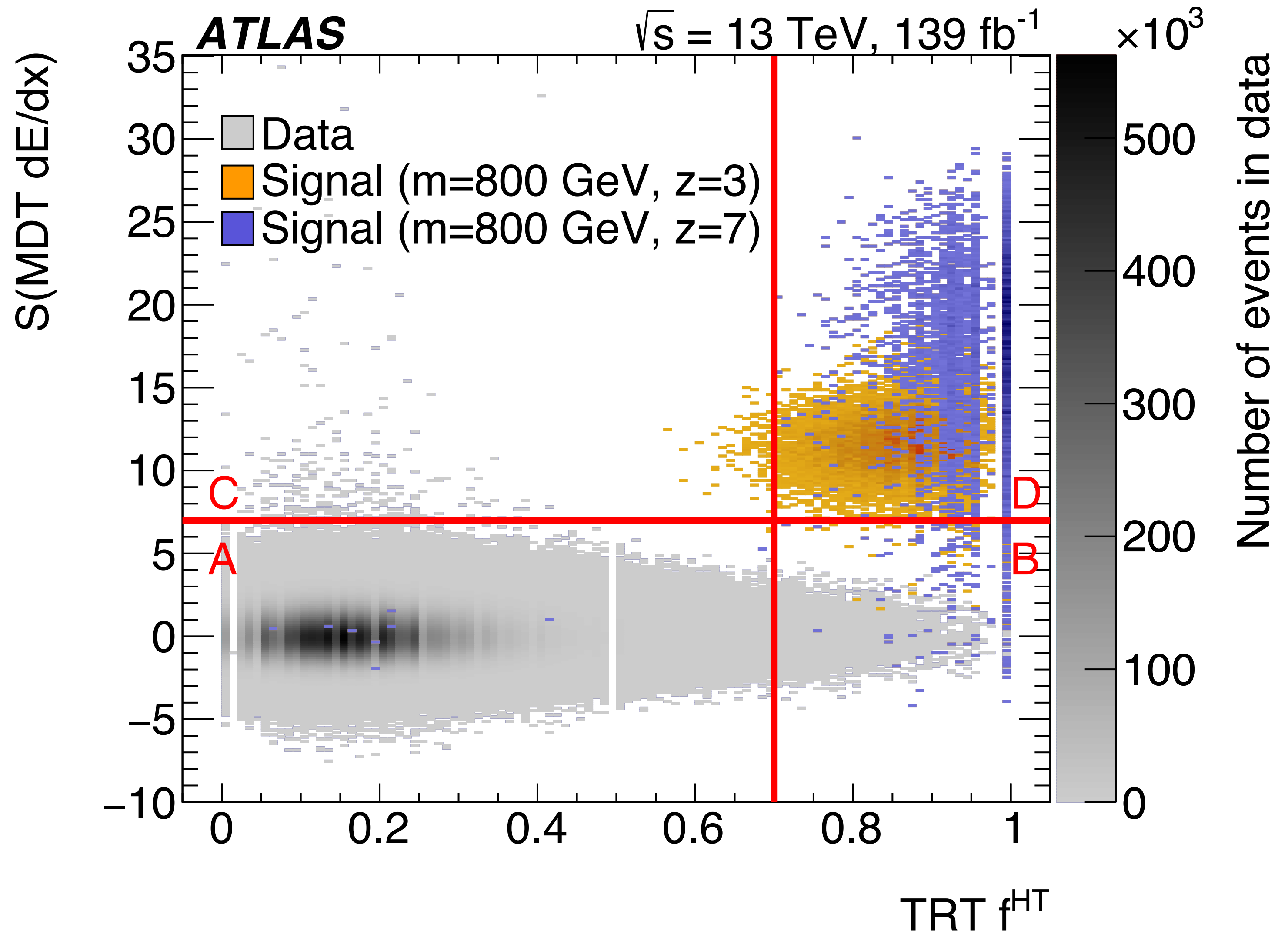


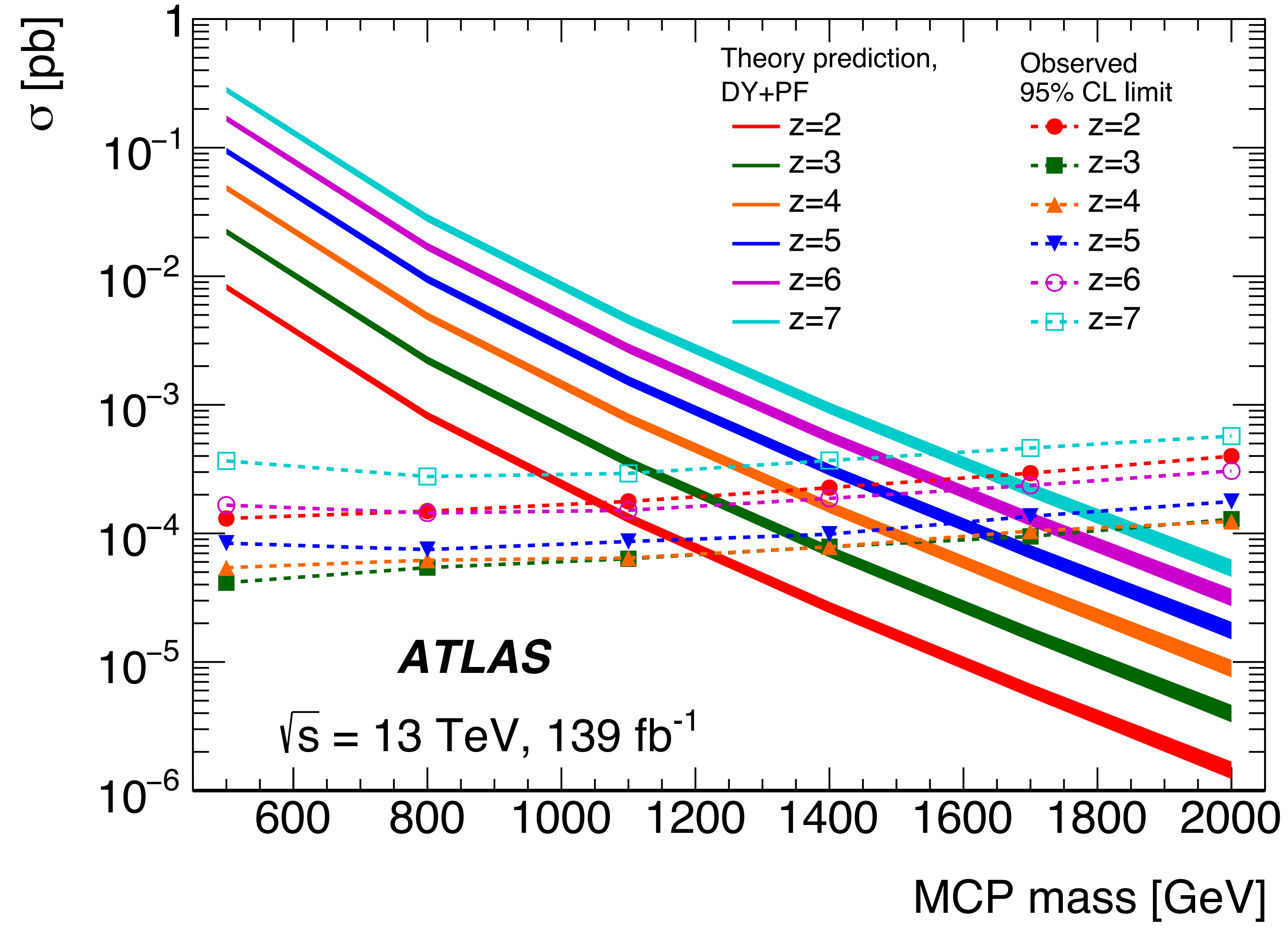
- Background mainly consists of:
  - high-pT muon reconstructed from several muons losing their energy in the same detector elements
  - sporadic-noise
- All background estimated by using a data-driven technique.

z=2



z>2





- $|q| = 2e$ particles excluded for m < 1060GeV
- $|q| = 6e$ particles excluded for m < 1600GeV